AN ABSTRACT OF THE THESIS OF

Andrea J. Bord for the degree of Master of Science in Forest Engineering presented on July 13, 2006.

Title: Field and Laboratory Strength Analysis of a Forest Road in NW Oregon and its Association with the Formation of Ruts

Abstract approved:

Kevin Boston

A one-mile section of a newly constructed forest road in Northwest Oregon was analyzed for various aspects of subgrade and surface strength and their association with the formation of ruts during the first hauling season. Field and laboratory tests were completed on the road and the road materials to determine general characteristics and potential for improved performance. Field testing included the Sand Cone test on the subgrade layer and the collection of Clegg impact values for the subgrade and surface layers. Laboratory tests included sieve analysis and Atterberg limits as well as California bearing ratio 15-point tests to determine the general soil characteristics and the potential strength of the material. The incidence of ruts was measured after the first hauling season and was used as the environmental performance variable. The results of this case study show that compaction of the subgrade was the most important aspect in providing strength to the road. Other soil properties were not found to influence the strength of the soil when compared to the compaction tests. Study results suggest that the potential strength of the soil was not achieved in the field, likely due to high water contents during construction. Conclusions on the association of the material properties and the formation of ruts cannot be drawn at this time.

Field and Laboratory Strength Analysis of a Forest Road in NW Oregon and its Association with the Formation of Ruts

by

Andrea J. Bord

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I understand that my thesis will become part of the permanent collection of the Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Andrea J. Bord, Author

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Field and Laboratory Strength Analysis of a Forest Road in NW Oregon and its Association with the Formation of Ruts

1 Introduction

Roads provide important access to forest resources. Without the access provided by roads, our forests cannot be properly managed for timber, or forest protection. Roads also greatly increase the opportunity for recreation activities in forest lands by providing access to lookouts, waterfalls, rivers and lakes that would otherwise be virtually inaccessible to the majority of the population. However, forest roads can be disruptive to many natural processes that exist within the forest including hillslope hydrology, hillslope stability, wildlife habitat, and water quality. The design, construction and maintenance of forest roads are vital components in minimizing the possible negative effects of forest roads while maintaining access to the forest.

1.1 Problems associated with Forest Roads

Forest roads have long been known for the negative environmental effects they have on forests. Forest roads have been found to contribute to an increase in the occurrence of debris flows and increased sediment to streams (Swanson and Dryness, 1975 and Cederholm and Reid, 1987). These negative environmental effects can be harmful to fish and other aquatic species as well as domestic water sources (Cederholm and Reid, 1987 and SAMAB, 1996). Proper precautions must be taken to lessen the negative environmental effects associated with forest roads.

The strength of a road can influence the amount of sediment that a road produces. Clearly, the way a road is designed and constructed can influence its strength. Increasing compaction of a soil subgrade is a way to increase soil strength characteristics and bearing capacity (Das, 2002, and Smith and Smith, 1998). Water content during compaction influences the degree of compaction that can be achieved (Das, 2002). It might be possible to minimize sediment from forest roads by controlling water content and compaction of soil subgrades during forest road design and construction.

Road maintenance is also very important in minimizing sediment from roads. Road crown geometry and the degree of rutting on the road surface are factors that contribute to sediment production from forest roads (Luce and Black, 1999). Regular maintenance will help to maintain the integrity of the road surface and the shape of the road crown, which will promote rapid drainage and resist rutting (Lord and Dreesen, 2005). Properly drained roads and those free of ruts do not produce as much sediment as those with ruts (Lord and Dreesen, 2005 and Reid and Dunne, 1984).

Weather conditions may greatly affect sediment production from roads. Soils are weakest when they are saturated. Some land managers may choose to close forest roads during wet conditions. However, it is important to remember that traffic in both wet and dry conditions is responsible for sediment production (Bilby et al., 1989). Roads built to high standards may help to reduce sediment production even if they are only used during dry seasons.

Roads can be one of the most significant costs in forest operations (Layton et al., 1992). The initial construction costs of forest roads are highly variable. A new road might cost as little as $5,000 per mile, or more than $100,000 per mile depending upon factors such as terrain, required equipment, and surfacing design (Layton et al., 1992). Annual maintenance costs are also highly variable. More durable roads may only cost the land owner $85 per mile per year, where a less durable road may be as much as $3300 per mile per year (USFS, 2005).

It is important to find cost-effective methods to improve the environmental performance of forest roads. Environmental regulations such as those under the Clean Water Act (CWA) may require higher standards for construction and maintenance of forest roads to minimize negative effects. These regulations can increase forest management costs. For example, in the Federal District Court case Pronsolino v. Marcus (1996), 91 F. Supp. 2d 1337 (and affirmed by the Ninth Appellate Court 291 F. 3d 1123, 2002 U.S. App.), the Pronsolinos estimated that complying with the Total Maximum Daily Load’s (TMDL’s) to regulate nonpoint source pollution on the Garcia River in Northern California reduced their financial returns by approximately $750,000

(Pronsolino v. Marcus, 1996/2002). Environmental protection regulations will likely increase forest management costs, while forest revenue remains the same.

Many states and federal agencies have implemented regulations or best management practices (BMPs) to help control negative environmental effects from forest roads. For instance, the California Forest Practice Rules (FPRs) require timber hauling operations to stop when forest roads become "saturated" (CDF, 2006). The Washington FPRs require that road construction is completed when moisture and soil conditions will not likely result in excessive erosion or soil movement (Washington DNR, 2006). Other states rely on the Environmental Protection Agency (EPA) national management measures to control nonpoint source pollution from forestry, which include BMPs that suggest that soil subgrades be compacted at the "proper" water content (EPA, 2005).

These regulations and guidelines require that the user have knowledge of site specific information such as when a road is "saturated," and what the "proper" water content is for compaction. Implementing these regulations and guidelines may help to reduce negative environmental impacts from forest roads, however they can be difficult to apply since site specific information is not often known.

1.2 Justification for Road Research

Forest road designs, unlike those for urban streets or highways, are often based on maximum grade and alignment criteria without any consideration of site specific geotechnical information. Typical design and construction practices for forest roads do not include site specific requirements such as targets for soil water content, lift thickness or density. Since there are no specific targets there is no ability to control construction practices for these properties.

Cost is a great concern to the forest industry. Generally it is assumed that site specific geotechnical testing would increase the cost of a new road beyond acceptable levels. However, the cost of gathering site specific geotechnical information would be small compared to the total cost for the new road. This information might also allow for adjustments to the original road design that may help to reduce the total road cost such as decreased depth of the aggregate surface layer. Having this information would also help to improve forest roads and reduce negative environmental effects from those roads. Clearly there is a need to develop a low-cost procedure that will allow for the collection of site specific geotechnical information before and during the construction of forest roads.

One of the problems to overcome is the variability and uncertainty in the natural forest environment. Soils can dramatically change from ridgetop soils that are typically shallow, to deep valley bottom soils. Changes in soil characteristics along a road alignment might require more than one road design to assure that negative environmental effects are minimized and that the road is not over-designed. With knowledge of site specific geotechnical information, it might be possible to identify weak areas and improve them before road deformation occurs. The potential decrease in negative environmental effects and the opportunity for savings in construction and maintenance costs by avoiding over-design and by decreasing maintenance frequency could mitigate the initial site investigation costs.

1.3 Purpose

The purpose of this study is to determine if and how forest roads can be improved through increased compaction of the soil subgrade. To determine if forest roads can be improved the variability of the road building materials must be understood. The strength of the road after construction compared to the potential strength observed in the laboratory will help determine the potential for improvement on this road. This study also considers deformation of the road in the form of ruts and the association of those ruts with the other variables measured. This project has begun to explore some potentially cost effective methods for gathering information about forest roads. Comparisons of results from low cost testing methods to more traditional higher cost testing methods may help find a cost effective way to improve forest roads while maintaining economic competitiveness.

1.4 Scope

This case study examined a one-mile road segment in the Oregon Coast Range from the summer of 2004 to the fall of 2005. The road was constructed during a wet period in the summer of 2004. A detailed analysis was completed including both field and laboratory testing on the subgrade and surface materials of the selected road. The results of this analysis may provide insight into the design of future road studies.

The remainder of this thesis contains a more in-depth justification of the purpose of the study, a description of the methods used for the study, results, and a discussion of the results and implications for future research.

2 Justification for Road Research

Forest roads provide the necessary access to forests for several reasons including management activities, recreation, and forest protection. Negative environmental effects associated with forest roads are an increasing concern for land managers. Current forest road design and construction practices do not incorporate specific site conditions that may help decrease negative environmental effects associated with roads. Building roads to higher standards to minimize negative environmental effects may be a very costly task for land owners and may reduce the economic competitiveness of the forest industry.

2.1 The Components of Forest Roads

Forest roads are made up of many components. The road prism is made up of two main components, the subgrade and the surface (figure 1). The subgrade of a forest road, or base layer, is usually constructed from native soil. Ideally, the soil is compacted and shaped to ensure proper drainage. Many forest roads are surfaced with an aggregate pavement. The aggregate surface is typically compacted and shaped in the same way as the subgrade. The basic road prism is designed to move water off of the road surface as quickly as possible while maintaining a safe and smooth running surface for vehicles (Wells, 2001). Commonly, road prisms are shaped to form crowned, insloped or outsloped road surfaces (Wells, 2001).

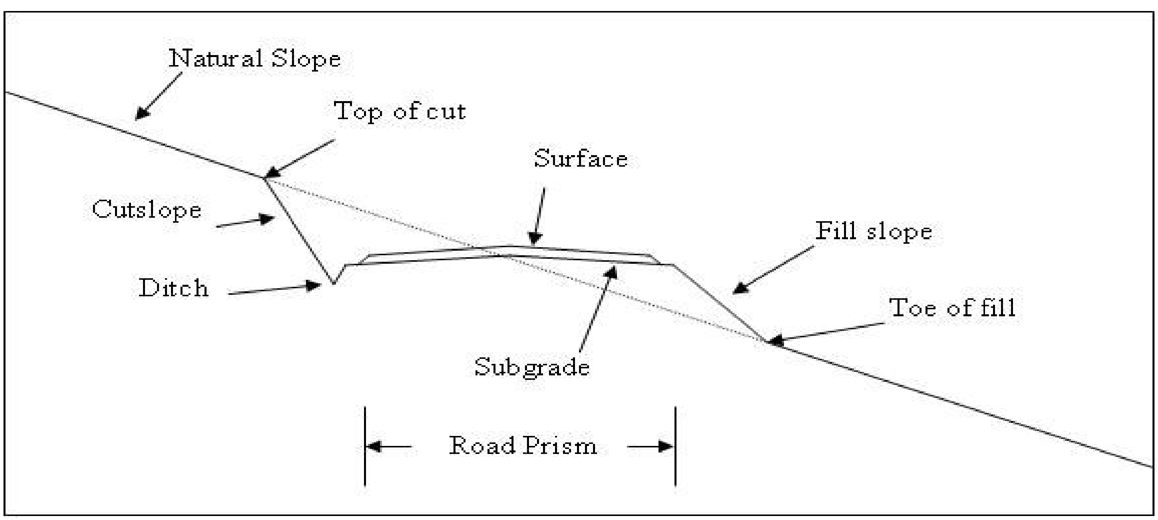

Figure 1. Diagram of a cross section of a typical crowned forest road

2.1.1 Subgrade

Soil subgrades are the foundation of roads. Weak subgrades lead to road failures often seen in the form of rutting. Fleming & Rogers (1993, as cited in Dawson, 1999) compared two theoretical subgrade materials with four different theoretical surfacing types and evaluated each combination for rutting. The stronger subgrade material (rubber on concrete) showed rutting only with the weakest surface material (sand and gravel). The weak subgrade (soft clay) showed rutting with all four surfacing materials. This comparison illustrates the importance of a strong subgrade in resisting deformation.

The type of material that makes up a subgrade can influence its strength and its performance. Foltz and Burroughs (1990) examined sediment production from rutted and non-rutted roads and determined that the range of values they observed was partially due to soil characteristics. Das (2002) states that soil strength from compaction is greatly influenced by soil type including its grain size distribution, shape of the soil grains, specific gravity, and clay content.

Natural characteristics of subgrade soils can often be summarized with the soil classification. Soils are typically classified by either the American Society for Testing and Materials (ASTM) standards or the American Association of State Highway and Transportation Officials (AASHTO) standards (ASTM D-2487-00, and AASHTO M 145-91). The ASTM classification is typically used for engineering purposes and the AASHTO classification is used for highway construction purposes (ASTM D-2487-00, and AASHTO M 145-91). These classifications can be determined through a series of laboratory tests and can often give an idea of the engineering properties of a soil, especially in the context of expansive clays. Soils with different general properties such as gradation, plasticity and classifications are expected to have different engineering, or strength, properties. In the context of forest roads this is important because inherently weak soil is more likely to rut and produce sediment than naturally strong soil. If these natural characteristics were determined in the laboratory prior to construction, it might be possible to tailor construction efforts to improve the overall soil strength characteristics and increase road performance.

In the forested environment, it is cost prohibitive to excavate and haul large quantities of undesirable material and replace it with material of more desirable characteristics. As mentioned before, Das (2002) explains that compaction of soils increases the strength characteristics of the soil which leads to increased bearing capacity. Water content during compaction influences the degree of compaction that can be achieved (Das, 2002). In order to achieve maximum soil strength and increase bearing capacity, a subgrade must be compacted at its optimum condition for a specific desired density.

Optimum conditions for compaction can be determined with laboratory tests. The standard and modified compaction tests are often used to determine the optimum water content for compaction and the resulting maximum dry unit weight for a given compactive energy (ASTM D 698 and ASTM 1557-00). These compaction tests are often referred to as the standard Proctor test and the modified Proctor test. The California bearing ratio (CBR) test uses compacted samples to evaluate the strength of the compacted soil after soaking the sample in water to simulate its weakest state (ASTM D 1883-99). If the optimum conditions from the laboratory tests are attained in the field a stronger road will result. These tests can seem costly however when compared to the total cost of designing and constructing a new road, the cost of the tests are relatively low. Implementing the laboratory test results in the field will not only provide a stronger road but will likely create an opportunity for decreases in construction and maintenance costs.

2.1.2 Surface

The surface of a road prism is equally as important as its subgrade. The aggregate surface of a forest road can be one of the most expensive elements of the road. Delivered aggregate may cost $15,000 to $30,000 per mile (Lovins et al., 2004). Land managers may be tempted to cut corners when it comes to aggregate quality in order to meet financial objectives. Bilby et al. (1989) illustrates that the quality of material used to surface roads affects the amount of sediment the road produces. The properties of the aggregate, such as hardness, percent sand, durability, and gradation, help define how the road will perform. Mills et al. (2003) recommends the use of aggregate with the lowest percentage of fines required to properly seal the road surface in order to reduce the amount of water that infiltrates the road prism.

2.2 Cost

Excavation costs for a common soil might be as low as $55 per station on flat ground with the addition of nearly $1.50 per cubic yard for slopes greater than 50% (Wilbrecht, 2000). Hauling costs for the excavated material are often a substantial portion of the total cost of road construction depending on the volume of endhaul material and the location of the disposal site (Wilbrecht, 2000). If the volume of excess soil to be hauled away from the construction site could be reduced, the cost of construction would most likely decrease. It might be possible that with increased compaction of the soil subgrade, the volume of endhaul material could be reduced. The results might include a lower total road cost and a stronger road subgrade.

Surfacing roads can also be a substantial portion of the total cost of road construction. As mentioned before, delivered aggregate can cost $15,000 to $30,000 per mile (Lovins et al. 2004). If the volume of aggregate required for the road surface could be reduced, the cost of the aggregate material as well as the cost of hauling would contribute to a lower total cost for construction. It might be possible that increasing subgrade strength through increased compaction could lead to thinner aggregate pavements greatly reducing the total aggregate volume required.

Maintenance of forest roads is a recurring cost for land managers however improving road surfaces contributes to decreases in sediment (Schiess et al., 2000). There is a careful balance between the amount of road maintenance required to minimize negative environmental effects of roads and the cost of that maintenance. It is likely that stronger, well constructed roads require less maintenance.

2.3 Ruts

Road failure can be seen in a variety of forms including ruts, potholes and corrugations. Road failures can originate from both subgrade and surface failures (Wardle, 1998). The strength of the road is dependent upon both the strength of the individual parts of the road as well as the interaction between those parts (Dawson, 1997). Typically, the design of forest roads does not include factors of subgrade strength, surface strength, or their interaction.

When evaluating the performance of a road, the strength of the road building materials is often overlooked. Failures in forest roads are easily observed in the degree of rutting observed on the road surface. Water concentrated in vehicle ruts has more energy to produce and transport sediment than water that is not concentrated in wheel ruts (Kahklen, 2001, and Gatto, 1999).

Dawson (1997) describes the stages of rutting observed on aggregate surfaced roads. "Mode 0" ruts come from compaction under traffic loading (Dawson, 1997). It might be possible to repair "Mode 0" rutting with road maintenance. Aggregate with inadequate shear strength may exhibit "Mode 1" rutting (Dawson, 1997). "Mode 1" ruts can be identified by the heave that results from the aggregate being displaced (Dawson, 1997). Increasing compaction may help to reduce this type of failure (Dawson, 1997). Dawson (1997) defines "Mode 2" rutting as failure in the subgrade. It is important to avoid "Mode 2" rutting if possible because repair of the soil subgrade on a road is much more difficult than repair of the surface. If subgrade strength could be improved, it might be possible to prevent "Mode 2" rutting.

2.*4* ***Current Practices and Future Possibilities for Forest Road Design and Construction***

Forest road design is commonly based on maximum grade and alignment restrictions rather than site specific information. Tests such as the laboratory Proctor compaction tests and CBR tests are often used on highway road projects to determine the conditions required to achieve high quality construction but there are no similar requirements for tests on forest roads. Most states in the Pacific Northwest (PNW) do not have regulations that require land managers to have detailed knowledge of site specific conditions of road building materials prior to construction. Instead regulations in most of the PNW manage risk by limiting behavior that may increase negative environmental effects from forest roads.

The California Forest Practice Rules (FPRs) instruct that fills are compacted in one foot increments (CDF, 2006). The State of Washington FPRs also requires that road fills be constructed in layers with compaction completed with tractors or other construction equipment (Washington DNR, 2006). Washington FPRs indicate the importance of soil water content by requiring that moisture conditions during construction are such that prevent excessive erosion (WA DNR, 2006). Oregon Forest Practice Rules require that forest roads are built with materials that will resist rutting and that if deep rutting occurs, hauling must be suspended (ODF, 2006).

Currently there are no requirements for standard geotechnical testing on forest road sites prior to construction. In some cases a road engineer will examine a site visually and make decisions for the road design and construction based on professional judgment. Designing and constructing forest roads based on site specific material properties would most likely help to increase the performance of roads. If specific soil characteristics are known before construction begins, construction can be tailored to suit the needs of the specific materials in order to optimize resources and minimize construction costs.

Currently on new forest roads, there is typically no design standard established or control during construction for water content and density. Often compaction is completed with vehicles such as crawler tractors that are designed to have low-ground pressure and offer little improvement in strength of the soil subgrade. Dump trucks might be used for further compaction. It might be possible to achieve up to 80% of maximum density when compacting with tractors and dump trucks although this is only possible under optimal soil conditions and when operators are careful to split their tracks (Kramer, 2001). If tractor and truck operators are not careful in splitting their tracks, the entire road surface may not receive the same amount of compaction. The inconsistencies in the degree of compaction may lead to “Mode 0” rutting as defined by Dawson (1997).

Soil water content is not controlled during the construction of forest roads. For example, the Oregon FPRs allow the construction of roads in wet conditions as long as sediment does not enter streams (ODF, 2006). On a typical highway construction project soil water content is adjusted, even if that means delay of construction, in order to achieve optimal conditions for compaction of the soil. For forest road construction, financial and time constraints may prohibit the adjustment of soil water content. If the demand for timber is high enough, roads can be constructed in the same season they are used for hauling timber no matter what the weather conditions. Soil that is compacted wet or dry of the optimum water content will not achieve as high a value for density or strength as soil compacted at optimum moisture levels (Das, 2002).

2.5 Opportunities for Improving Forest Roads

Reducing negative environmental effects from forest roads is a continuous objective for land managers. Many roads will contain weak spots that will produce more sediment than the rest of the road. These weak spots have a higher chance of failure by developing ruts or potholes (EPA, 2000). Assuming weak points in a road can be identified, it might be cost effective to treat these sites differently than the entire road. Luce and Black (1999) believe that managing a smaller number of high risk sites would be the most efficient way to control sediment production. Bilby et al. (1989) adds that concentrating efforts on the few sites that have the highest potential of producing and delivering sediment to streambeds might lessen the negative effects from roads. If construction efforts are focused on areas with naturally weak soils or high risk sites, the road might be improved without the added cost of over-designing the entire road or increasing maintenance frequency. The benefits of this practice may out-weigh the costs.

Isolated weak points may be associated with natural material variability or poor design and construction practices. Natural variability in road building materials makes designing and understanding forest roads more difficult. In order to get a grasp on the natural variability of a site, the correct sampling intensity must be selected. More research is needed in this area to be confident in classifying and characterizing road building materials in order to increase environmental performance.

Variation in construction quality may contribute to poor road performance. One way of controlling this variability is through quality control using standards set prior to construction. In-situ measurements taken during construction operations may help identify areas that need improvement. However more research is needed to determine which tests will be most beneficial and cost effective for forest roads.

It might also be beneficial to compare results of in-situ testing to those from laboratory testing for the same materials. This comparison might reveal the cause of isolated weaknesses and methods for avoiding these weaknesses. It is possible that comparisons between laboratory and field test results will lead to the construction of stronger, more environmentally sound roads. However, further research is needed to develop these relationships.

3 Methods

3.1 Overview

This case study examined one selected road on the Oregon Coast Range before, during and after its construction. No attempt has been made to expand the results of this case study to all roads in the Pacific North West (PNW). Field testing was completed on the subgrade and surface materials of the selected road. Traffic estimates and measurements of road deformation on the selected road were collected after the first year of hauling timber. Laboratory testing was completed on both the subgrade and surface materials of the selected road.

The tests selected were used to show a complete view of the current construction practices used for this road. This testing series also gave an improved view of the materials used for the road and their performance potential.

3.2 Study Site and Sampling Procedures

The study site was selected based on location, time of construction, and cooperation from the agency in charge, Oregon Department of Forestry (ODF). The study site was located in sections 9, 10, 11, 15, and 16 of T4N, R7W of the W.M. in the Clatsop State Forest, Clatsop County, Oregon (figures 2 and 3). The National Resources Conservation Services (NRCS) soil map indicates that the study site soil is a Rinearson silt loam with slopes from three to 30 percent on part of the study site and slopes from 30 to 60 percent on the remainder (NRCS 1988). The NRCS soil survey did not indicate the soil classification.

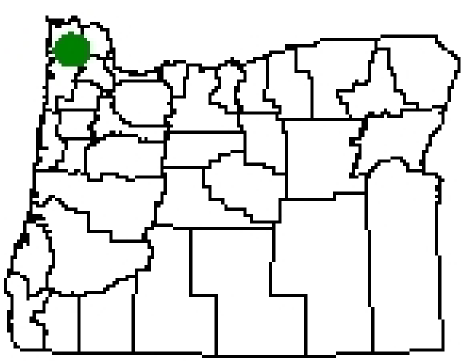

Figure 2. Map of Oregon counties with study site location in Clatsop County highlighted in green.

Figure 3. Aerial photograph of study site with study road drawn in red.

The study road was constructed during a wet period in the summer of 2004. The following list outlines the order and approximate time in which each stage of construction and testing was completed.

- Subgrade construction – July, 2004
- Subgrade sample collection – July, 2004
- Subgrade field testing – August, 2004
- Surface construction and aggregate sample collection – August, 2004
- Surface field testing – August, 2004
- Hauling of timber on road – August, 2004 to December, 2004
- Survey of road surface for ruts – December, 2004
- Laboratory sample preparation and testing – August, 2004 to April, 2006

The subgrade was constructed and compacted with a vibratory roller in July, 2004. The road was divided into 18, 300-foot sections over approximately one mile of road. Samples of the road materials were collected in the summer of 2004 for field and laboratory testing. Subgrade material was collected from random locations over the width of the road from the top 12 inches of material at each station in July, 2004. Collecting the subgrade material directly from the road prism eliminated any variability that may have existed in the soils surrounding the road.

Representative aggregate samples were collected from stockpiles during rocking operations for both the base coarse aggregate and the surfacing aggregate in August, 2004. The base coarse material used on the surface of the study road was crushed to a three inch maximum size, and the surface material was a crushed to a ¾ inch maximum size. The aggregate stockpiles were made up of rock originating from only one source. Each aggregate was crushed in a single operation which helped to maintain a uniform size distribution. These procedures helped to assure that the aggregate stockpiles contained uniform material. The aggregate samples were collected during loading operations from a number of stockpiles within the quarry that were used on the road. This allowed for aggregate sample collection in a safe manner that minimized interference with construction activities.

3.3 Field Testing

3.3.1 Field Subgrade Testing

3.3.1.1 Sand Cone Test

Testing of the soil subgrade in the field was completed in August, 2004 prior to surfacing of the road. The soil subgrade field water content and unit weight were measured using the Sand Cone method in accordance to American Society for Testing and Materials method D 1556-00 (ASTM D 1556-00). The Sand Cone method was chosen for this project because it is an easy way to get an accurate measure of field soil conditions. The Sand Cone method is less expensive and requires less training than some of the alternative testing methods such as the nuclear density gage (ASTM D 3017-01 and ASTM D 2922-01). Moisture contents were obtained in accordance to ASTM D

2216-98. Using the Sand Cone method at each station should give a reasonable estimate of after-construction density and moisture conditions of the soil subgrade.

3.3.1.2 Clegg Impact Values

The in-place soil subgrade impact values were obtained in August, 2004 prior to the surfacing of the road using the 20-kg Clegg impact hammer. The Clegg impact values (CIV's) were obtained in accordance to ASTM D 5874-02. The CIV was chosen as the field strength measurement of the subgrade because it is a low cost, easy to use tool. Three CIV's were recorded at each 100-foot interval down the length of the road. The left and right side CIV's were taken at the approximate location of the wheel rut of future traffic. The center CIV was taken near the center of the cross section of the road. The CIV's provide an index of the in-place soil subgrade strength following construction.

3.3.2 Field Surface Testing

3.3.2.1 Clegg Impact Values

The in-place aggregate surface impact values were obtained using the 20-kg Clegg impact hammer following the surfacing of the road in August, 2004. The CIV's were obtained in accordance to ASTM D 5874-02. As with the subgrade, the CIV was chosen as the field strength measurement for the surface because it is a low cost, easy to use tool. Three CIV's were recorded at each 100-foot interval down the length of the road. The left and right side CIV's were taken at the approximate location of the wheel rut of future traffic. The center CIV was taken near the center of the cross section of the road.

3.3.2.2 Road Survey for Deformation

Upon the completion of logging and hauling over the selected road in December, 2004, a detailed survey was conducted at each station. Approximately 3.5 million board feet (MMBF) of logs (about 740 log trucks) was hauled on the study road. This traffic is equivalent to approximately 4841 Equivalent Single Wheel Loads (ESWL's) (based on the conditions outlined in Appendix C, table C-2). Survey data were gathered at two foot increments across the width of the road at each station using profile leveling techniques. Ruts were defined as a deformation in the road surface of 0.2 feet or more. The detailed survey was completed to determine the absence or presence of ruts in each road section that occurred since the construction of the road.

3.4 Laboratory Testing

3.4.1 Laboratory Subgrade Testing

The soil samples were prepared for testing in the laboratory. After the samples were air dried, the material was processed down to its particle size. This was accomplished with mechanical and manual methods. There is no ASTM standard for processing soil with mechanical grinding methods. However, the amount of soil required for the planned laboratory tests (over 100 pounds of soil per station) made it infeasible to use exclusively manual methods as recommended by ASTM (mortar and pestle, ASTM D 421-85). Mechanical grinding methods also helped to standardize the processing of the soil samples so that each of the 17 samples was processed an equal amount. In most cases, after mechanical grinding, the soil could be processed further when ground with a mortar and pestle. For this study, it was assumed that mechanical grinding methods did not change the soil structure in such a manner that the test results were affected. Future studies of a similar nature may help to determine the effects that mechanical grinding methods had on the test results.

3.4.1.1 Sieve Analysis, Atterberg Limits, and Soil Classification

Laboratory testing of the soil subgrade samples included sieve analysis and Atterberg limits for the purpose of classification. All sieve analyses were completed in accordance to ASTM D 421-85 and ASTM D 422-63 with the exception of the sample preparation as mentioned before. Atterberg limits were obtained in accordance to ASTM D 4318-00. Classification of soils was determined using the Unified Soil Classification System (USCS) following ASTM D 2487-00, and using the AASHTO classification system following AASHTO M 145-91. These testing methods were chosen to measure the general characteristics of the subgrade soil material because they are widely used and recognized. The purpose of these tests and classifications was to determine the variability of the soil over the length of the road study site as well as the general characteristics of each soil sample.

3.4.1.2 California Bearing Ratio 15-Point Test

Soaked, 15-point CBR tests were completed on all soil samples. These tests closely followed ASTM D 1883-99. The CBR test procedure was chosen to measure the strength of the subgrade soil material because it is widely used and recognized index of soil strength. The ASTM standard procedure calls for only soil passing the ¾ inch (in.) sieve. The standard procedure also says that the material retained on the ¾ in sieve is to be removed and replaced with material passing the ¾ in. sieve and retained on the No.4 sieve. Because of the nature of this material, which was typically an SM or SC when classified by the USCS, there was not enough material retained on the No. 4 sieve in a reasonably sized sample to replace the material retained on the ¾ in. sieve. Therefore, for this study the material retained on the ¾ in. sieve was replaced with material passing the ¾ in. sieve.

All CBR samples were compacted according to ASTM D 1557-00 using compactive energies of 56, 25, and 10 blows per layer as suggested by ASTM D 1883-99. The highest and lowest compactive energies are approximately equal to the standard and modified compaction efforts defined by ASTM D 698-00 and ASTM D 1577-00 respectively. For the remainder of this thesis these compaction levels will be referred to as the standard Proctor and modified Proctor compaction levels. A surcharge weight of 25 pounds (lbs) was used for all CBR tests. This surcharge weight was chosen because it represents the stresses that would be induced by 12 inches of aggregate surfacing using an aggregate unit weight of 125 pounds per cubic foot (pcf).

The compaction data from the 15-point CBR test for each soil sample was plotted. From these curves, the optimum water content for compaction and its corresponding maximum dry unit weight were determined. The results from the CBR penetration test were labeled on the compaction curves. Two optimum CBR values were chosen for further analysis; the maximum observed CBR value at each of the three compaction levels, and the CBR value which corresponded to the optimum water content and maximum dry unit weight for each of the three compaction levels. In some cases both of these values were the same.

3.4.2 Laboratory Surface Material Testing

Laboratory aggregate testing included a sieve analysis accordance to ASTM C 136-96a. The purpose of the sieve analysis was to show the general characteristics of the aggregate being used for the road surface. The results from the sieve analysis were compared to the literature reviewed for this study to determine if the aggregate was of good quality.

3.5 Missing Observations

One difficulty in doing research on an active construction site is accessibility. For this reason, not all data sets collected were complete. The laboratory soil data was missing one sample because the sample location was occupied by heavy machinery during the day of collection making the material unavailable. The location of the road made it impractical to return to the site and collect the missing subgrade material before the road was surfaced. The 17 samples that were collected and tested appeared to give a complete picture of the road subgrade material and its variability.

Other data sets that had missing data points included the rutting data and the Sand Cone data. The rutting data was missing from stations 11 and 12 because unscheduled road maintenance occurred during the survey. Sand Cone density measurements were not taken at stations 4, 6, 11, and 12 because those areas were not accessible on the day of testing. The data that were collected were used in comparing field observations to laboratory observations.

3.6 Data Analysis and Justification of the Methods Used

All statistical analysis for this study was completed using the S-plus software package. A data set was compiled that included several test results for the purpose of data snooping. Data snooping is a form of unplanned comparison where only values of particular interest are examined with statistical tests. The justification for data snooping in this study comes from the premise that there is little known about the engineering properties of specific road building materials prior to construction of forest roads. The testing methods used in this study attempt to evaluate specific road building materials and their performance. In order to better understand site specific information to benefit future road building endeavors, it is important to determine what correlations, if any, exist between road building materials and the testing results from this study. These results might lead to more cost effective road building procedures. For instance if correlations are detected, it might be possible to replace the more expensive and time consuming tests such as the 15-point CBR tests, with less expensive tests such as sieve analysis and still achieve estimates of soil strength.

The compiled data set included the sample name, and the general soil properties for each soil sample including classification, percent passing the No. 200 sieve, and Atterberg limits. This data set also included the soil strength variables for each of the three compactive energies for each soil sample (optimum water content, maximum dry unit weight, maximum CBR and the CBR value corresponding to the maximum dry unit weight). This data set was analyzed for correlations between general soil properties and the soil strength variables. Significant correlations between this data might reveal opportunities for low cost testing methods to be used to determine soil strength characteristics. This analysis was completed using two-dimensional scatter plots, matrix plots, correlation matrices, linear regressions and the Kruskal-Wallis rank test (a non-parametric test similar to an analysis of variance).

The 15-point CBR data were compared to the USCS soil classifications to determine if the strength properties of the soil were different for soils with different classifications. The USCS classification was chosen because it is the one typically used for engineering purposes where AASHTO classification is typically used for highway construction projects (ASTM D 2487-00 and AASHTO M 145-91). It was assumed in this case that forest roads more closely resemble an engineering project than a highway project.

The results of the 15-point CBR testing series were used to determine the potential bearing strength of the road building materials including the optimum water content for maximum compaction. The results from the laboratory CBR testing series at the standard Proctor level was compared to several other field and laboratory test results.

The standard Proctor level was chosen for this analysis because it is often used as a standard on earthwork projects (Das, 2002).

The strength potential determined in the laboratory by the CBR results at the standard Proctor level was compared to the Sand Cone results to determine if the design and construction of the road may have been improved. The CBR results were also compared to the sieve analysis and Atterberg limits for each soil to determine if simpler laboratory tests might explain some of the variation in the more complicated CBR tests.

The average of the subgrade CIV’s from the right and left sides was used for further analysis because it was thought that any traffic on the road since the time of construction should be considered additional compaction. The subgrade CIV’s were compared to laboratory 15-point CBR test results to determine if CIV after construction can explain anything about the variation in soaked laboratory CBR. Correlations between these variables may help to identify low cost tools to supplement or replace higher priced testing methods.

The subgrade CIV’s were also compared to the results from the soil sieve analyses, and the Atterberg limits results to determine if the general soil properties may indicate anything about the subgrade CIV’s obtained after construction. The results from the survey measuring deformation of the road after the first season of hauling were compared to the CIV’s from the subgrade and surface to determine if the soil strength index measured with the Clegg hammer after construction might indicate anything about the location of ruts.

4 Results

4.1 Overview

The results of this study indicate that the design and construction of this road could have been improved. Considerable variability can be seen in the water contents and maximum dry unit weights between the laboratory results and the field results. Other soil properties were not found to significantly explain the strength in terms of the density, water content or CBR of the soil.

The density measurements from the Sand Cone method showed the strength of each soil sample at its in-situ condition prior to the surfacing of the road. The California bearing ratio (CBR) 15-point test results showed the potential strength for each soil sample at a given compactive energy. The laboratory and in-situ testing results from the subgrade material showed that the potential strength of the soil was not achieved in the field at the time of construction. Rutting was observed on six of 18 road segments after approximately 3.5 million board feet (MMBF) of logs was hauled on the study road.

4.2 In-situ Results

4.2.1 Subgrade Test Results

The in-place soil subgrade dry unit weights ranged from 45 pounds per cubic foot (pcf) to 78 pcf, with water contents ranging from 27% to 55%. The Sand Cone results were compared to the optimum water content and maximum dry unit weight from the laboratory test at the standard Proctor level. The field water contents were higher than the laboratory optimums (figure 4). The field dry unit weights were lower than the laboratory dry unit weights (figure 5). From these results it appears that the density of the soil subgrade could have been improved with increased design standards and control of water content and compaction during construction.

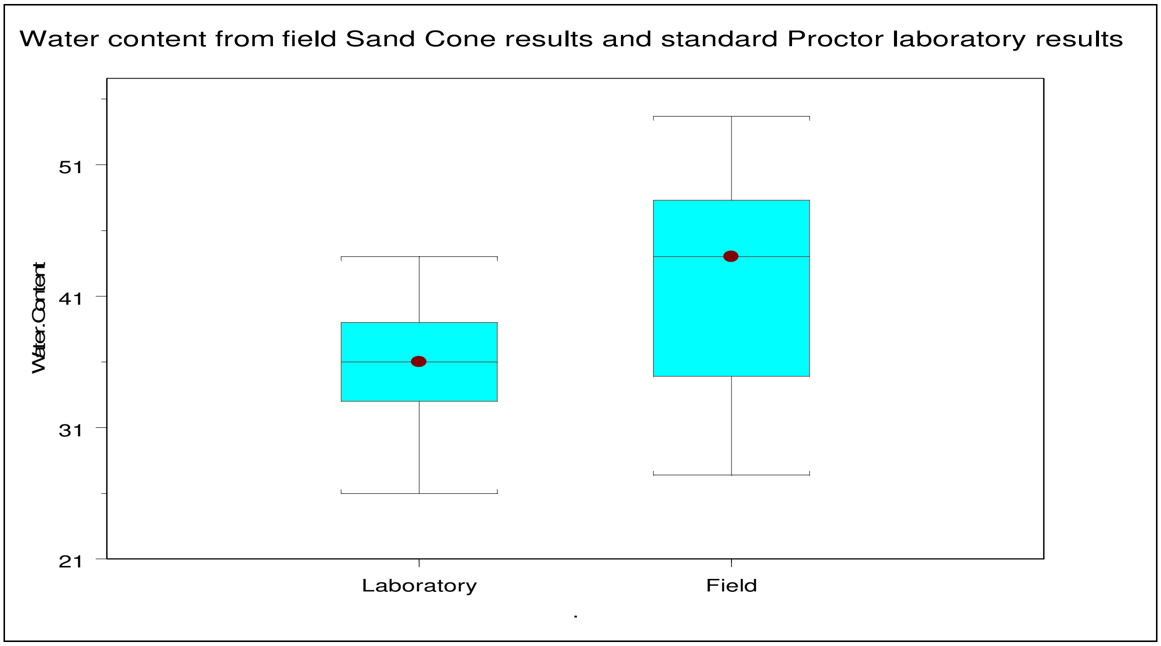

Figure 4. Field water content prior to construction of the surface layer of the road compared to laboratory optimum water content for the standard Proctor compaction level.

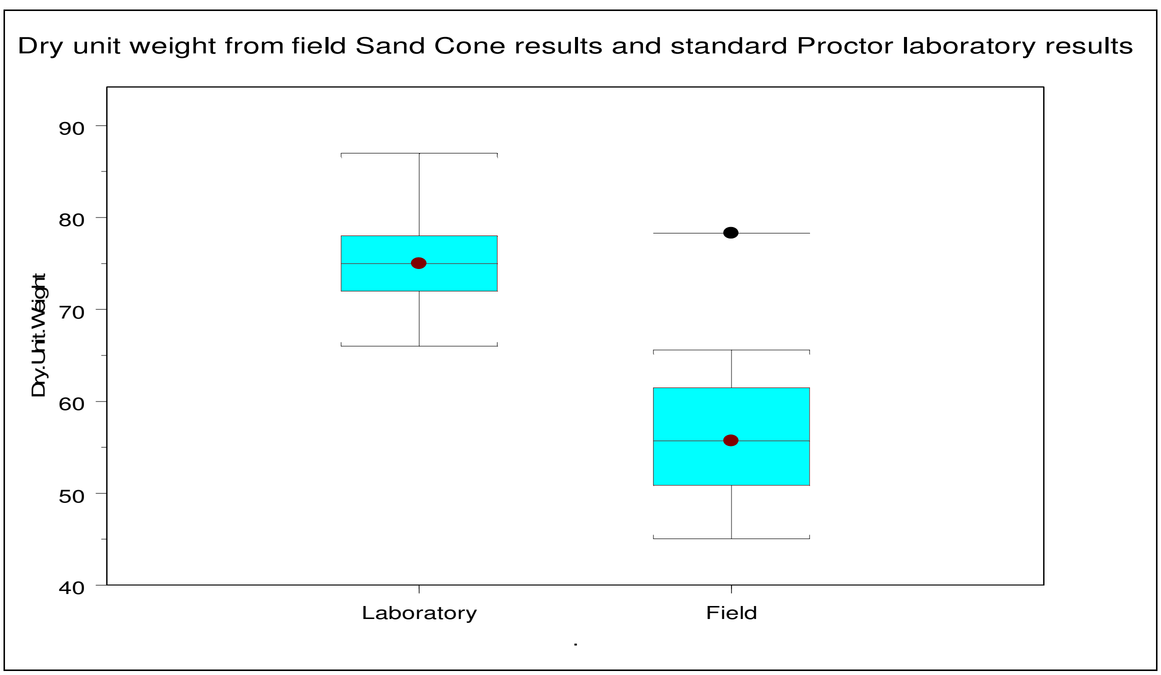

Figure 5. Field maximum unit weight prior to construction of the surface layer of the road compared to laboratory maximum unit weight for the standard Proctor compaction level.

4.2.2 Surface Testing Results

The average of the right and left side surface CIV's were compared to the center surface CIV. Figure 6 shows the difference in CIV between the average of the sides and the center of the surface. The increased CIV's from the average of the sides compared to the center can likely be attributed to increased compaction that resulted from the construction traffic.

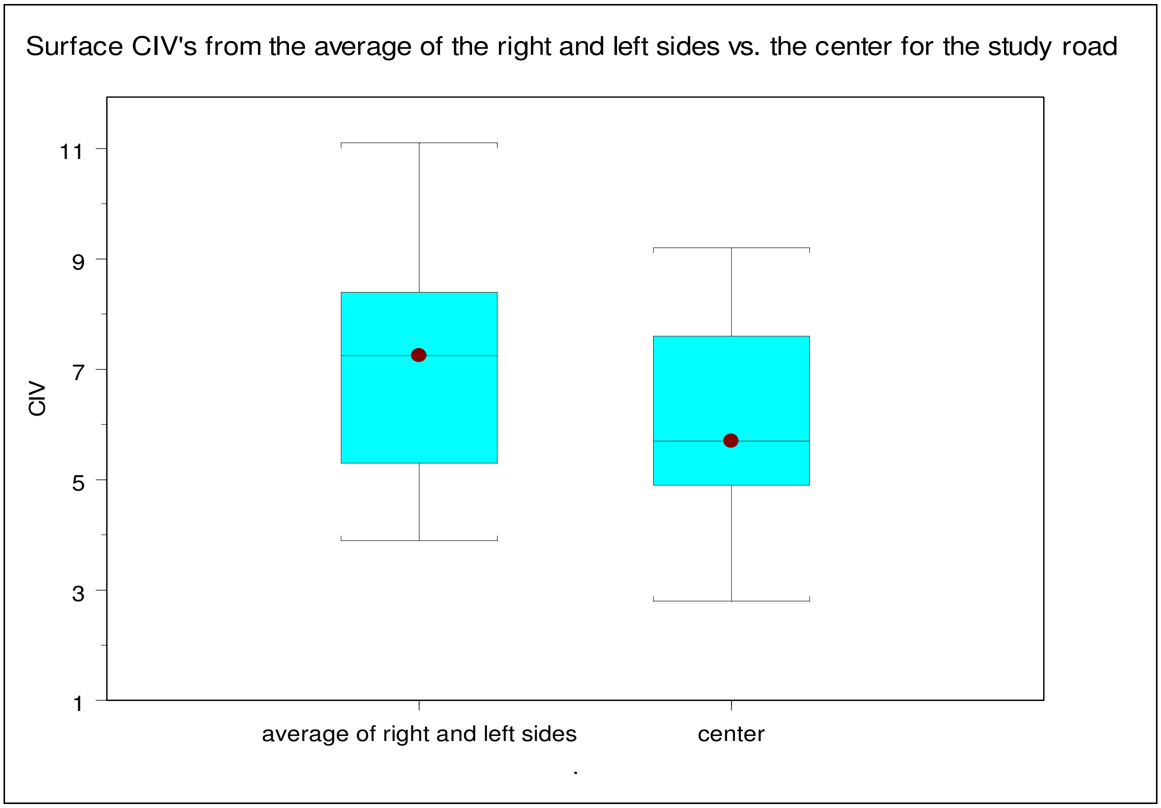

Figure 6. Surface Clegg impact values from the center and from the average of the right and left sides.

Upon the completion of logging and hauling over the selected road, a survey was conducted at each station to determine the presence or absence of ruts in each section. Rutting was observed on six of the 18 road segments. The CIV's, from the rutted and non-rutted segments were compared to determine if the CIV's for the rutted segments were significantly different from the non-rutted segments. Specifically, the null hypothesis Ho was tested against the alternative hypothesis Ha using the Kruskal-Wallis rank test with an alpha level of 0.05 where,

Ho: $CIV_{rut} = CIV_{no\text{-}rut}$

Ha: $CIV_{rut} \neq CIV_{no\text{-}rut}$

$\chi^2 = 1.115$, df = 1, p-value = 0.29

Result = Fail to reject Ho

The results of this test fail to reject Ho that there is no significant difference in the average of the CIV's from the right and left sides of the road between rutted and non-rutted road segments.

The same statistical analysis was completed for the surface CIV for rutted and non-rutted road segments. The null hypothesis Ho was tested against the alternative hypothesis Ha using the Kruskal-Wallis rank test with an alpha level of 0.05 where,

Ho: $CIV_{surface,\ rut} = CIV_{surface,\ no\text{-}rut}$

Ha: $CIV_{surface,\ rut} \neq CIV_{surface,\ no\text{-}rut}$

$\chi^2 = 0.12$, df = 1, p-value = 0.73

Result = Fail to reject Ho

The results of this test fail to reject Ho that there is no significant difference in the surface CIV between rutted and non-rutted road segments.

4.3 Laboratory Results

4.3.1 General Soil Properties

The sieve analysis results showed a wide range of percentages passing each sieve size (Appendix B.1 figure B-1 to figure B-21). The percent passing the No. 200 sieve ranged from seven to 26% (Appendix B figure B-21). The Atterberg limits told a similar story with plasticity indexes ranging from one to 12, liquid limits ranging from 28 to 43, and plastic limits ranging from 21 to 42 (Appendix B.2 figure B-22 to figure B-24). From these results, six different AASHTO classifications and five different Unified Soil Classification System (USCS) classifications were found on the road. Of the five USCS and six AASHTO classifications found for the soil samples, all were very similar in nature, typically fine sands. Table 1 shows the soil classifications by both methods according to sample station.

Table 1. Soil classifications by both USCS and AASHTO methods, percent passing the No. 200 sieve, and Atterberg limits for each soil sample

Sample	USCS	AASHTO	Percent passing No. 200	Liquid Limit	Plastic Limit	Plasticity Index
TM 1	SW-SM	A-1b	6.55	36.67	35.20	1.47
TM 2	SC	A-2-6	12.64	33.12	20.96	12.16
TM 3	SW-SM	A-1b	7.92	34.85	32.03	2.82
TM 4	SW-SC	A-2-4	10.82	32.16	24.50	7.66
TM 5	SW-SC	A-2-6	10.35	40.42	28.35	12.07
TM 6	SM	A-2-5	14.02	41.88	37.04	4.84
TM 7	SM	A-2-4	18.56	32.56	25.80	6.75
TM 8	SM	A-2-4	22.36	39.94	38.54	1.40
TM 9	SM	A-2-4	26.31	35.46	34.28	1.18
TM 10	SM	A-2-4	12.87	36.63	29.68	6.95
TM 11	SM	A-2-4	15.70	35.05	33.59	1.46
TM 12	SM	A-1b	16.43	37.08	34.79	2.29
TM 14	SC	A-3	19.09	34.44	25.93	8.51
TM 15	SM	A-1b	15.82	38.16	36.91	1.25
TM 16	SW-SM	A-1b	9.79	37.79	36.19	1.59
TM 17	GW-GM	A-1a	10.56	42.80	41.76	1.04
TM 18	SM	A-2-4	18.44	27.54	25.48	2.06

4.3.2 California Bearing Ratio 15-Point Test Results

The results of the 15-point CBR testing series showed the potential soil compaction including the optimum water content and resulting maximum dry unit weight, as well as the subsequent bearing strength for each soil sample. It was expected that the CBR 15-point tests would follow text book patterns. For a given soil, as compaction energy increases from standard Proctor (10 blows per lift) to modified Proctor (56 blows per lift), the maximum dry unit weight is expected to increase while the optimum water content is expected to decrease (Das, 2002). As expected, increases in compactive energy from standard Proctor (10 blows per lift) to modified Proctor (56 blows per lift), resulted in increases in maximum dry unit weight and decreases in optimum water content. As optimum water content decreased, maximum dry unit weight and CBR increased.

For all CBR 15-point results two plots were constructed. The compaction plot shows the water content against the dry unit weight for the soil at the time of compaction. A zero air voids curve was calculated using an assumed specific gravity of 2.7 (figure 7). This curve illustrates the maximum dry unit weight possible for a soil with a specific gravity of 2.7. As data points approach the zero air voids curve (ZAV), the sample approaches maximum density. This curve was included on all compaction plots to illustrate the density achieved by the laboratory compaction efforts relative to the maximum density for the assumed specific gravity of 2.7.

The second plot created for each sample was the CBR plot (figure 8). This plot showed the water content at time of compaction compared to the observed CBR value for each test. Typical compaction and CBR plots are shown in figures 7 and 8. The compaction and CBR plots for the remaining 16 samples can be seen in Appendix A.

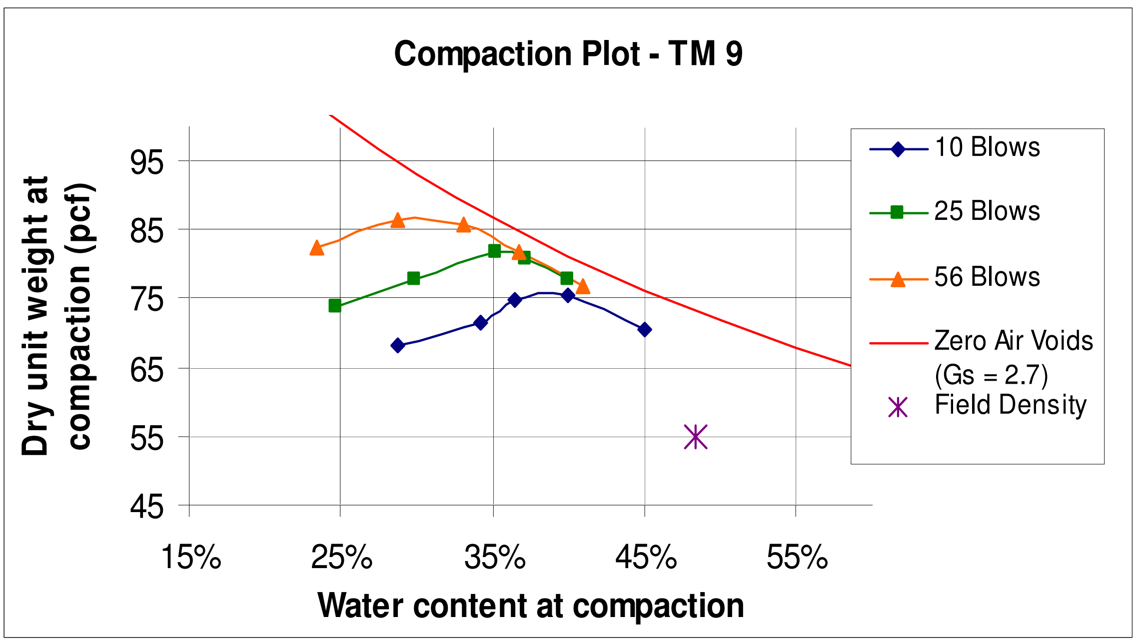

Figure 7. Compaction plot for sample TM 9 showing compaction water content and resulting dry unit weight for three compaction levels from the laboratory, the zero air voids curve using a specific gravity of 2.7, and the field dry unit weight observed with the Sand Cone method.

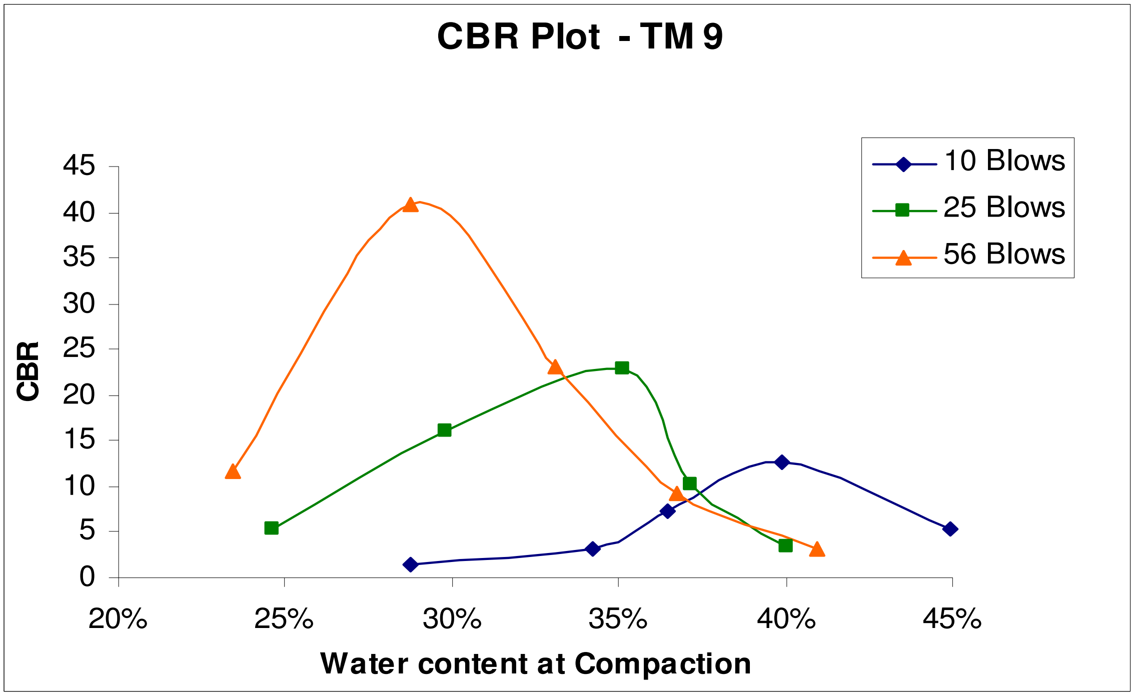

Figure 8. CBR plot for sample TM 9 showing water content at compaction and observed CBR value for all three compaction levels from the laboratory testing.

4.4 Results of Data Snooping

Data snooping was preformed on the test results for this study. The goal of the data snooping in this case was to determine what correlation, if any, existed among the test results that might allow for the substitutions of simpler, less expensive tests for more costly and complicated tests. If for example, the percent passing the No. 200 sieve was strongly correlated to the optimum water content at a given compaction level, it might be possible to use a simple and inexpensive sieve analysis instead of multiple compaction tests to determine the optimum water content for a given soil. Likewise, if the plasticity index was strongly correlated to the CBR value then it might be possible to explain soil strength using relatively inexpensive Atterberg limit tests instead of more costly and time consuming CBR tests.

A matrix plot and a correlation table were created using the data snooping data (Appendix B.4 figure B-26 and table B-1). Through visual inspection, it did not appear that any obvious relationships were present between general soil properties and the soil strength variables from the laboratory tests.

4.4.1 Kruskal-Wallis Rank Tests

4.4.1.1 Comparison of Compaction Levels

The Kruskal-Wallis rank test was completed to determine if soil strength parameters were significantly different for samples at different compactive energies. The null hypothesis was tested, using an $\alpha = 0.05$, that there is no significant difference in optimum water content between the three compaction levels.

Ho: Optimum Water Content $_{10}$ = Optimum Water Content $_{25}$ = Optimum Water Content $_{56}$

Ha: Optimum Water Content $_{10}$ ≠ Optimum Water Content $_{25}$ ≠ Optimum Water Content $_{56}$

$\chi^2 = 15.35$, df = 2, p-value = 0.0005

Result = Reject Ho

The results of the Kruskal-Wallis rank test rejected the null hypothesis that there is no statistically significant difference in optimum water content between the three compaction levels.

The null hypothesis was tested, using an $\alpha = 0.05$, that there is no significant difference in maximum dry unit weight between the three compaction levels.

Ho: Maximum Dry Unit Weight $_{10}$ = Maximum Dry Unit Weight $_{25}$ = Maximum Dry Unit Weight $_{56}$

Ha: Maximum Dry Unit Weight $_{10}$ ≠ Maximum Dry Unit Weight $_{25}$ ≠ Maximum Dry Unit Weight $_{56}$

$\chi^2 = 25.88$, df = 2, p-value = 0

Result = Reject Ho

The results of the Kruskal-Wallis rank test rejected the null hypothesis that there is no statistically significant difference in maximum dry unit weight between the three compaction levels.

The null hypothesis was tested that there is no significant difference in maximum observed CBR value between the three compaction levels using an $\alpha = 0.05$.

Ho: Maximum CBR $_{10}$ = Maximum CBR $_{25}$ = Maximum CBR $_{56}$

Ha: Maximum CBR $_{10} \neq$ Maximum CBR $_{25} \neq$ Maximum CBR $_{56}$

$\chi^2 = 44.46$, df = 2, p-value = 0

Result = Reject Ho

The results of the Kruskal-Wallis rank test rejected the null hypothesis that there is no statistically significant difference in maximum observed CBR value between the three compaction levels.

The null hypothesis was tested, using an $\alpha = 0.05$, that there is no significant difference in the CBR value corresponding to maximum dry unit weight between the three compaction levels.

Ho: CBR at Maximum Unit Weight $_{10}$ = CBR at Maximum Unit Weight $_{25}$ = CBR at Maximum Unit Weight $_{56}$

Ha: CBR at Maximum Unit Weight $_{10} \neq$ CBR at Maximum Unit Weight $_{25} \neq$ CBR at Maximum Unit Weight $_{56}$

$\chi^2 = 39.62$, df = 2, p-value = 0

Result = Reject Ho

The results of the Kruskal-Wallis rank test rejected the null hypothesis that there is no statistically significant difference in the CBR value corresponding to maximum dry unit weight between the three compaction levels.

The results of these tests indicate that for all of the soil strength parameters, there is a statistically significant difference between at least two of the compaction levels and that the data set must remain separated by compaction level for other analyses.

4.4.1.2 Comparison of Soil Classifications

The Kruskal-Wallis rank test was completed to determine if soil strength parameters were significantly different for soils with different USCS classifications. The null hypothesis was tested that there is no significant difference in optimum water content between soils with different classification at each compaction level using an $\alpha = 0.05$.

Ho: Optimum Water Content $_{SW\text{-}SM\ i}$ = Optimum Water Content $_{SC\ i}$ = Optimum Water Content $_{SW\text{-}SC\ i}$ = Optimum Water Content $_{SM\ i}$ = Optimum Water Content $_{GW\text{-}GM\ i}$

Ha: Optimum Water Content $_{SW\text{-}SM\ i}$ ≠ Optimum Water Content $_{SC\ i}$ ≠ Optimum Water Content $_{SW\text{-}SC\ i}$ ≠ Optimum Water Content $_{SM\ i}$ ≠ Optimum Water Content $_{GW\text{-}GM\ i}$

Where, i = 10, 25, and 56

$\chi^2_{10} = 4.68$, $df_{10} = 4$, p-value $_{10} = 0.32$

$\chi^2_{25} = 5.08$, $df_{25} = 4$, p-value $_{25} = 0.28$

$\chi^2_{56} = 2.48$, $df_{56} = 4$, p-value $_{56} = 0.65$

Result = Fail to reject Ho at all compaction levels

The results of the Kruskal-Wallis rank test fail to reject the null hypothesis for each compaction level that there is no statistically significant difference in optimum water content between soils of different classifications.

The null hypothesis was tested, using an $\alpha = 0.05$, that there is no significant difference in the maximum dry unit weight between soils with different classification at each compaction level.

Ho: Maximum Unit Weight $_{SW\text{-}SM\ i}$ = Maximum Unit Weight $_{SC\ i}$ = Maximum Unit Weight $_{SW\text{-}SC\ i}$ = Maximum Unit Weight $_{SM\ i}$ = Maximum Unit Weight $_{GW\text{-}GM\ i}$

Ha: Maximum Unit Weight $_{SW\text{-}SM\ i}$ ≠ Maximum Unit Weight $_{SC\ i}$ ≠ Maximum Unit Weight $_{SW\text{-}SC\ i}$ ≠ Maximum Unit Weight $_{SM\ i}$ ≠ Maximum Unit Weight $_{GW\text{-}GM\ i}$

Where, i = 10, 25, and 56

$\chi^2_{10} = 1.14$, $df_{10} = 4$, p-value $_{10} = 0.89$

$\chi^2_{25} = 0.87$, $df_{25} = 4$, p-value $_{25} = 0.93$

$\chi^2_{56} = 2.75$, $df_{56} = 4$, p-value $_{56} = 0.60$

Result = Fail to reject Ho at all compaction levels

The results of the Kruskal-Wallis rank test fail to reject the null hypothesis for each compaction level that there is no statistically significant difference in the maximum dry unit weight between soils of different classifications.

The null hypothesis was tested, using an $\alpha = 0.05$, that there is no significant difference in the maximum CBR value between soils with different classification at each compaction level.

Ho: Maximum CBR $_{SW\text{-}SM\ i}$ = Maximum CBR $_{SC\ i}$ = Maximum CBR $_{SW\text{-}SC\ i}$ = Maximum CBR $_{SM\ i}$ = Maximum CBR $_{GW\text{-}GM\ i}$

Ha: Maximum CBR $_{SW\text{-}SM\ i}$ ≠ Maximum CBR $_{SC\ i}$ ≠ Maximum CBR $_{SW\text{-}SC\ i}$ ≠ Maximum CBR $_{SM\ i}$ ≠ Maximum CBR $_{GW\text{-}GM\ i}$

Where, i = 10, 25, and 56

$\chi^2_{10} = 4.99$, $df_{10} = 4$, $p\text{-value}_{10} = 0.29$

$\chi^2_{25} = 2.33$, $df_{25} = 4$, $p\text{-value}_{25} = 0.68$

$\chi^2_{56} = 2.16$, $df_{56} = 4$, $p\text{-value}_{56} = 0.71$

Result = Fail to reject Ho at all compaction levels

The Kruskal-Wallis rank test failed to reject the null hypothesis for each compaction level that there is no statistically significant difference in the maximum CBR value between soils of different classifications.

The null hypothesis was tested that there is no significant difference in the CBR value corresponding to maximum dry unit weight between soils with different classification at each compaction level.

Ho: CBR at Maximum Unit Weight $_{SW\text{-}SM\ i}$ = CBR at Maximum Unit Weight $_{SC\ i}$ = CBR at Maximum Unit Weight $_{SW\text{-}SC\ i}$ = CBR at Maximum Unit Weight $_{SM\ i}$ = CBR at Maximum Unit Weight $_{GW\text{-}GM\ i}$

Ha: CBR at Maximum Unit Weight $_{SW\text{-}SM\ i}$ ≠ CBR at Maximum Unit Weight $_{SC\ i}$ ≠ CBR at Maximum Unit Weight $_{SW\text{-}SC\ i}$ ≠ CBR at Maximum Unit Weight $_{SM\ i}$ ≠ CBR at Maximum Unit Weight $_{GW\text{-}GM\ i}$

Where, i = 10, 25, and 56

$\chi^2_{10} = 4.68$, $df_{10} = 4$, $p\text{-value}_{10} = 0.32$

$\chi^2_{25} = 8.00$, df $_{25} = 4$, p-value $_{25} = 0.09$

$\chi^2_{56} = 1.64$, df $_{56} = 4$, p-value $_{56} = 0.80$

Result = Fail to reject Ho at all compaction levels

The results of the Kruskal-Wallis rank test, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level that there is no statistically significant difference in the CBR value corresponding to maximum dry unit weight between soils of different classifications.

The results of these tests indicate that for all of the soil strength parameters, there is no statistically significant difference between soils with different classifications. For this reason the soil data will not be separated by classification.

4.4.2 Regression Tests

Several two-dimensional scatter plots and simple linear regressions were analyzed to search for correlations between the properties of the road building materials and the testing methods used in this study. All simple linear regressions follow the form y = a + bx using an alpha level of 0.05 to test if the slope, b, is statistically significantly different from zero. No strong correlations were found between the variables in the data snooping set. The entire array of scatter plots can be seen in Appendix B.

<u>4.4.2.1 Percent Passing the No. 200 Sieve Relating to Soil Strength Properties</u>

Simple linear regressions were performed, using an $\alpha = 0.05$, on the percent passing the No. 200 sieve and each of the four soil strength parameters (optimum water content, maximum dry unit weight, maximum observed CBR, and the CBR value corresponding to the maximum dry unit weight) at each compaction level to determine if soil grain size distribution explains anything about the soil strength properties. The four groups of regression results can be seen on pages 34-36.

Test 1:

Independent variable = Percent Passing the No. 200 Sieve

Dependent variable = Optimum Water Content $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 3.00, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.10

F-stat $_{25}$ = 1.81, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.20

F-stat $_{56}$ = 0.39, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.54

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the percent passing the No. 200 sieve cannot explain a statistically significant amount of the variability in optimum water content at any compaction level (Appendix B.4 figure B-27 to figure B-29).

Test 2:

Independent variable = Percent Passing the No. 200 Sieve

Dependent variable = Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, $b = 0$

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 0.08, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.78

F-stat $_{25}$ = 0.14, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.72

F-stat $_{56}$ = 0.49, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.49

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the percent passing the No. 200 sieve cannot explain a statistically significant amount of the variability in maximum dry unit weight at any compaction level (Appendix B.4 figure B-30 to figure B-32).

Test 3:

Independent variable = Percent Passing the No. 200 Sieve

Dependent variable = Maximum CBR $_i$

Where, i = 10, 25, and 56

Ho: Slope, $b = 0$

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 4.77, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.05

F-stat $_{25}$ = 1.24, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.28

F-stat $_{56}$ = 1.49, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.24

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the percent passing the No. 200 sieve cannot explain a statistically significant amount of the variability in maximum CBR at any compaction level (Appendix B.4 figure B-33 to figure B-35).

Test 4:

Independent variable = Percent Passing the No. 200 Sieve

Dependent variable = CBR at Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, $b = 0$

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 3.86, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.07

F-stat $_{25}$ = 0.67, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.43

F-stat $_{56}$ = 0.07, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.80

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the percent passing the No. 200 sieve cannot explain a statistically significant amount of the variability in CBR corresponding to the maximum dry unit weight at any compaction level (Appendix B.4 figure B-36 to figure B-38).

4.4.2.2 Plasticity Index Relating to Soil Strength Properties

Simple linear regressions were completed on the plasticity index and the four soil strength variables at each compaction level to determine if plasticity index explains anything about the soil strength variables. The results of these four groups of tests can be seen on pages 37-39.

Test 1:

Independent variable = Plasticity Index

Dependent variable = Optimum Water Content $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.84, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.37

F-stat $_{25}$ = 0.01, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.92

F-stat $_{56}$ = 1.16, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.30

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plasticity index cannot explain a statistically significant amount of the variability in optimum water content at any compaction level (Appendix B.4 figure B-39 to figure B-41).

Test 2:

Independent variable = Plasticity Index

Dependent variable = Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.11, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.75

F-stat $_{25}$ = 0.54, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.47

F-stat $_{56}$ = 0.35, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.56

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plasticity index cannot explain a statistically significant amount of the variability in maximum dry unit weight at any compaction level (Appendix B.4 figure B-42 to figure B-44).

Test 3:

Independent variable = Plasticity Index

Dependent variable = Maximum CBR $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b $\neq$ 0

F-stat $_{10}$ = 0.07, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.80

F-stat $_{25}$ = 0.06, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.82

F-stat $_{56}$ = 0.22, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.65

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plasticity index cannot explain a statistically significant amount of the variability in maximum CBR at any compaction level (Appendix B.4 figure B-45 to figure B-47).

Test 4:

Independent variable = Plasticity Index

Dependent variable = CBR at Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b $\neq$ 0

F-stat $_{10}$ = 0.91, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.36

F-stat $_{25}$ = 0.79, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.39

F-stat $_{56}$ = 6.68, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.02

Result = Fail to reject Ho $_{10}$

Fail to reject Ho $_{25}$

Reject Ho $_{56}$,

Resulting equation with $R^2 = 0.31$,

CBR at Max Dry Unit Weight $_{56}$ = 44.46 – 1.40 * Plasticity Index

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for the standard Proctor and middle compaction levels. The conclusion from these tests is that the plasticity index cannot explain a statistically significant amount of the variability in CBR corresponding to the maximum dry unit weight at the standard Proctor level or the middle compaction level (Appendix B.4 figure B-48 and figure B-49). The results from the regression test on the modified Proctor compaction level reject the null hypothesis. Thirty-one percent of the variation in the CBR value corresponding to the maximum dry unit weight can be explained by plasticity index (Appendix B.4 figure B-90). Generally, for this case, as Plasticity index increased, the CBR value corresponding to the optimum water content for the modified Proctor compaction level decreases.

4.4.2.3 Liquid Limit Relating to Soil Strength Properties

Simple linear regressions were completed on the liquid limit and the soil strength variables at each compaction level to determine if liquid limit explains anything about the soil strength variables. The four groups of regression results can be seen on pages 39-41.

Test 1:

Independent variable = Liquid Limit

Dependent variable = Optimum Water Content $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 2.18, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.16

F-stat $_{25}$ = 1.98, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.18

F-stat $_{56}$ = 1.61, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.22

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the liquid limit cannot explain a statistically significant amount of the variability in optimum water content at any compaction level (Appendix B.4 figure B-50 to figure B-52).

Test 2:

Independent variable = Liquid Limit

Dependent variable = Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 3.09, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.10

F-stat $_{25}$ = 2.33, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.15

F-stat $_{56}$ = 2.65, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.13

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an α = 0.05, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the liquid limit cannot explain a statistically significant amount of the variability in maximum dry unit weight at any compaction level (Appendix B.4 figure B-53 to figure B-55).

Test 3:

Independent variable = Liquid Limit

Dependent variable = Maximum CBR $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.49, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.49

F-stat $_{25}$ = 0.36, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.56

F-stat $_{56}$ = 3.05, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.10

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an α = 0.05, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the liquid limit cannot explain a statistically significant amount of the variability in maximum CBR at any compaction level (Appendix B.4 figure B-56 to figure B-58).

Test 4:

Independent variable = Liquid Limit

Dependent variable = CBR at Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.06, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.82

F-stat $_{25}$ = 2.62, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.13

F-stat $_{56}$ = 0.35, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.57

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the liquid limit cannot explain a statistically significant amount of the variability in the CBR value corresponding to maximum unit weight at any compaction level (Appendix B.4 figure B-59 to figure B-61).

4.4.2.4 Plastic Limit Relating to Soil Strength Properties

Simple linear regressions were completed on the plastic limit and the soil strength variables at each compaction level to determine if plastic limit explains anything about the soil strength variables. The four groups of regression results can be seen on pages 41-43.

Test 1:

Independent variable = Plastic Limit

Dependent variable = Optimum Water Content $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.10, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.75

$F\text{-stat}_{25} = 0.68$, $df_{25} = 1$ and 15, $p\text{-value}_{25} = 0.42$

$F\text{-stat}_{56} = 0.01$, $df_{56} = 1$ and 15, $p\text{-value}_{56} = 0.92$

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plastic limit cannot explain a statistically significant amount of the variability in optimum water content at any compaction level (Appendix B.4 figure B-62 to figure B-64).

Test 2:

Independent variable = Plastic Limit

Dependent variable = Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, $b = 0$

Ha: Slope, $b \neq 0$

$F\text{-stat}_{10} = 0.74$, $df_{10} = 1$ and 15, $p\text{-value}_{10} = 0.41$

$F\text{-stat}_{25} = 0.22$, $df_{25} = 1$ and 15, $p\text{-value}_{25} = 0.65$

$F\text{-stat}_{56} = 0.37$, $df_{56} = 1$ and 15, $p\text{-value}_{56} = 0.55$

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plastic limit cannot explain a statistically significant amount of the variability in maximum dry unit weight at any compaction level (Appendix B.4 figure B-65 to figure B-67).

Test 3:

Independent variable = Plastic Limit

Dependent variable = Maximum CBR $_i$

Where, i = 10, 25, and 56

Ho: Slope, $b = 0$

Ha: Slope, $b \neq 0$

$F\text{-stat}_{10} = 0.41$, $df_{10} = 1$ and 15, $p\text{-value}_{10} = 0.53$

$F\text{-stat}_{25} = 0.06$, $df_{25} = 1$ and 15, $p\text{-value}_{25} = 0.82$

F-stat $_{56}$ = 0.57, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.46

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plastic limit cannot explain a statistically significant amount of the variability in maximum CBR at any compaction level (Appendix B.4 figure B-68 to figure B-70).

Test 4:

Independent variable = Plastic Limit

Dependent variable = CBR at Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 0.21, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.65

F-stat $_{25}$ = 2.88, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.11

F-stat $_{56}$ = 1.15, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.30

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the plastic limit cannot explain a statistically significant amount of the variability in the CBR value corresponding to maximum unit weight at any compaction level (Appendix B.4 figure B-71 to figure B-73).

4.4.2.5 Clegg Impact Values Relating to Soil Strength Properties

The Clegg impact values measured in the field were regressed against maximum dry unit weight, maximum CBR, and the CBR value corresponding to the maximum dry unit weight at each compaction level. Significant relationships observed in these comparisons might indicate that CIV can be a useful tool in estimating laboratory soil strength properties. If this were the case, it might be possible to obtain CIV's during road construction for quality control purposes. The three groups of regression results can be seen on pages 44-45.

Test 1:

Independent variable = CIV

Dependent variable = Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 2.70, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.12

F-stat $_{25}$ = 4.05, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.06

F-stat $_{56}$ = 4.32, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.06

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the CIV cannot explain a statistically significant amount of the variability in maximum dry unit weight at any compaction level (Appendix B.4 figure B-74 to figure B-76).

Test 2:

Independent variable = CIV

Dependent variable = Maximum CBR $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.23, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.64

F-stat $_{25}$ = 4.51, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.05

F-stat $_{56}$ = 0.53, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.48

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the CIV cannot explain a statistically significant amount of the variability in maximum CBR at any compaction level (Appendix B.4 figure B-77 to figure B-79).

Test 3:

Independent variable = CIV

Dependent variable = CBR at Maximum Dry Unit Weight $_i$

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat $_{10}$ = 0.01, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.94

F-stat $_{25}$ = 3.11, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.10

F-stat $_{56}$ = 0.15, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.71

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the CIV cannot explain a statistically significant amount of the variability in the CBR value corresponding to maximum unit weight at any compaction level (Appendix B.4 figure B-80 to figure B-82).

4.4.2.6 Clegg Impact Values Relating to General Soil Properties

The Clegg impact values were also plotted against other soil properties to check for correlations. The two regression results can be seen on pages 45-46.

Test 1:

Independent variable = Percent Passing the No. 200 Sieve

Dependent variable = CIV

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat = 7.87, df = 1 and 15, p-value = 0.01

Result = Reject Ho

Resulting equation with $R^2 = 0.34$,

CIV = 10.94 – 0.25 * Percent Passing the No. 200 Sieve

The results of the simple linear regression tests, using an $\alpha = 0.05$, reject the null hypothesis. The conclusion from this test is that 34% of the variability in CIV can be explained by the percent passing the No. 200 sieve (Appendix B.4 figure B-91). Generally, with increasing fines, CIV decreases.

Test 2:

Independent variable = Plasticity Index

Dependent variable = CIV

Ho: Slope, b = 0

Ha: Slope, b ≠ 0

F-stat = 1.90, df = 1 and 15, p-value = 0.19

Result = Fail to reject Ho

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis. The conclusion from this test is that the plasticity index cannot explain a statistically significant amount of the variability in CIV (Appendix B.4 figure B-83).

4.4.3 Summary of Statistical Findings

A summary of the statistical findings for the tests preformed on the data for this study shows that out of multiple comparisons there were very few statistically significant relationships found (table 2). The soil strength variables include the optimum water content, maximum dry unit weight, maximum CBR, and CBR corresponding to maximum dry unit weight. The three compaction levels are the standard Proctor level, the middle level, and the modified Proctor level.

Table 2. Summary table of statistical results

Test	Comparison	Result
Kruskal-Wallis rank test	Subgrade CIV for rutted and non-rutted segments	**Fail to reject Ho**
Kruskal-Wallis rank test	Surface CIV for rutted and non-rutted segments	**Fail to reject Ho**
Kruskal-Wallis rank test	Soil strength variables between compaction levels	**Reject Ho** for all soil strength variables
Kruskal-Wallis rank test	Soil strength variables between USCS soil classifications at each compaction level	**Fail to reject Ho** for all soil strength variables at all compaction levels
Regression test	Percent passing the No. 200 sieve and soil strength variables at each compaction level	**Fail to reject Ho** for all soil strength variables at all compaction levels
Regression test	Plasticity index and soil strength variables at each compaction level	**Fail to reject Ho** for optimal water content, maximum dry unit weight, and maximum CBR at all compaction levels
		Fail to reject Ho for CBR at maximum dry unit weight for standard Proctor and middle compaction levels
		Reject Ho for CBR at maximum dry unit weight for modified Proctor compaction level
Regression test	Liquid limit and soil strength variables at each compaction level	**Fail to reject Ho** for all soil strength variables at all compaction levels
Regression test	Plastic limit and soil strength variables at each compaction level	**Fail to reject Ho** for all soil strength variables at all compaction levels
Regression test	Subgrade CIV and maximum dry unit weight, maximum CBR, and CBR at maximum dry unit weight at each compaction level	**Fail to reject Ho** for maximum dry unit weight, maximum CBR, and CBR at maximum dry unit weight at all compaction levels
Regression test	Percent passing the No. 200 sieve and subgrade CIV	**Reject Ho**
Regression test	Plasticity index and subgrade CIV	**Fail to reject Ho**

4.4.4 Field vs. Laboratory Soil Strength Observations

The water content and dry unit weight measurements from the Sand Cone analysis and the laboratory CBR compaction tests were plotted according to station distance down the road. These plots (figures 9 and 10) illustrate that the optimal conditions determined in the laboratory were not achieved in the field at the time of construction on many of the sample sites. The water contents measured in the field were consistently higher than the optimum water contents determined in the laboratory. The dry unit weight measurements from the field at the time of construction were much lower than the maximum dry unit weight achieved in the laboratory using the same soils.

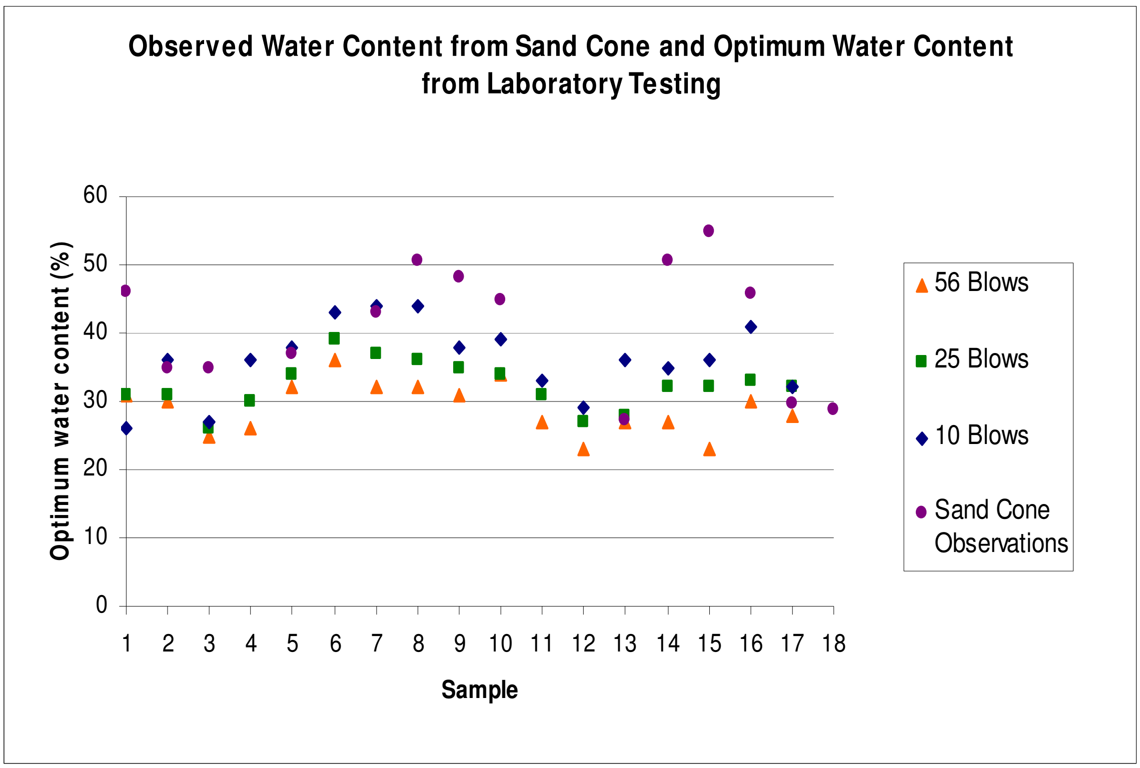

Figure 9. Observed field water content at each station from the Sand Cone results prior to surfacing of the road and the laboratory optimum water contents from the laboratory compaction results.

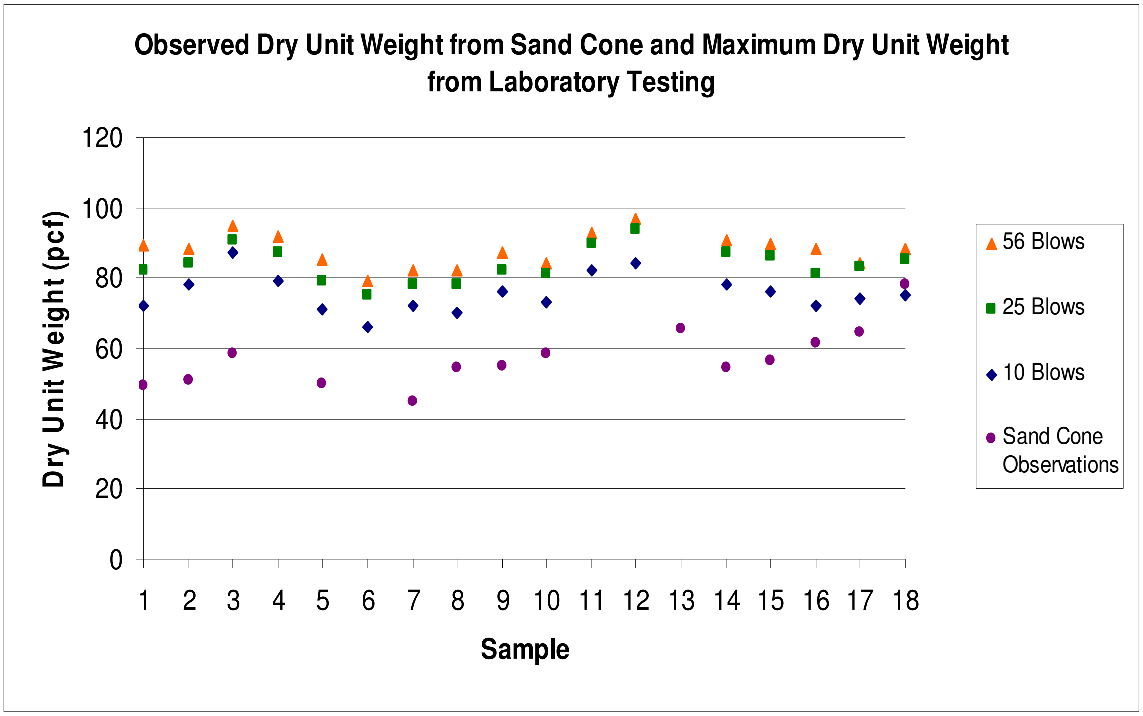

Figure 10. Observed field dry unit weight at each station from the Sand Cone results and laboratory maximum dry unit weights from the laboratory compaction results.

The laboratory CBR values were plotted according to station distance down the road. These plots (figures 11 and 12) illustrate the variability in CBR in among the soil samples and between compaction levels. The average of the maximum CBR's for each compaction level were nine, 25, and 45 for the standard Proctor, middle, and modified Proctor compaction levels respectively. The average of the CBR's corresponding to the maximum dry unit weight for each compaction level were eight, 24, and 38 for the standard Proctor, middle, and modified Proctor compaction levels respectively.

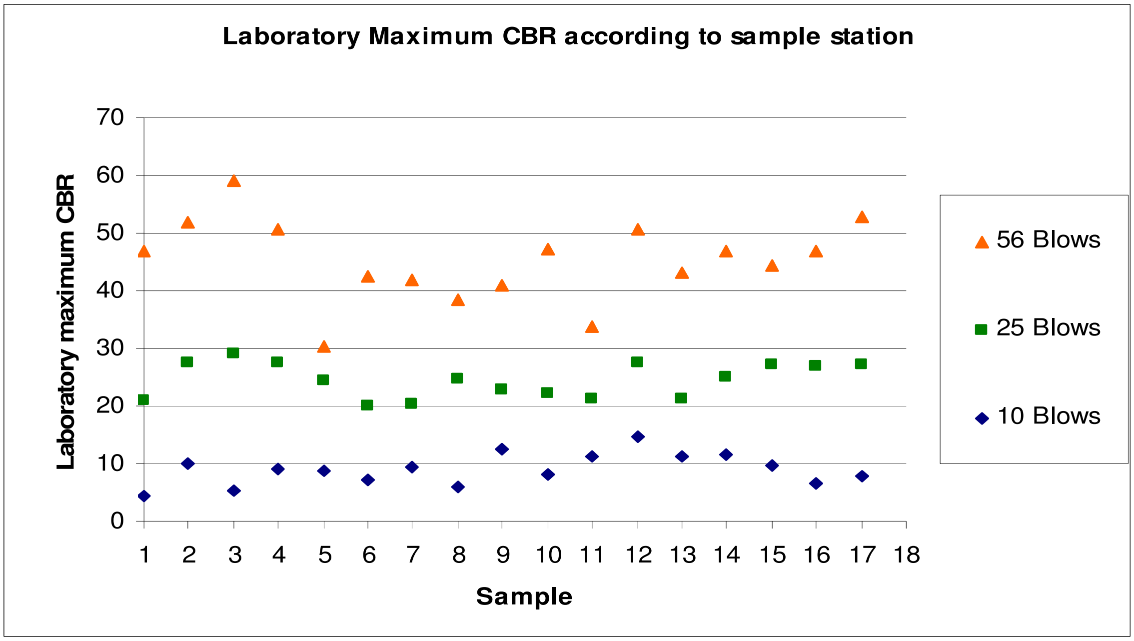

Figure 11. Laboratory maximum CBR according to sample station

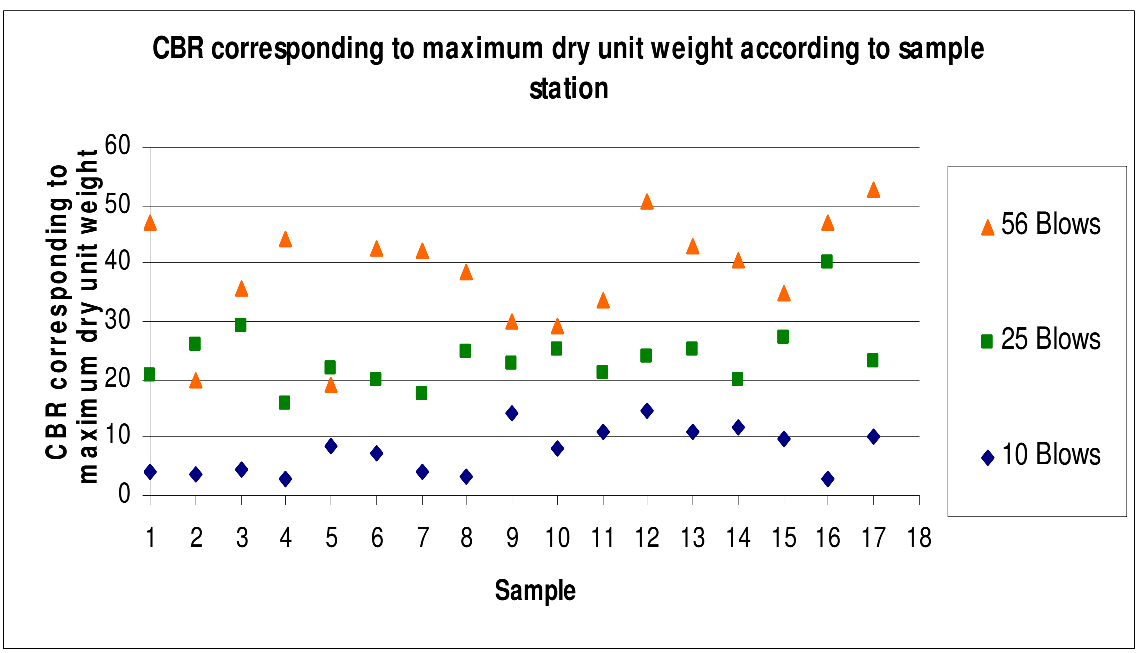

Figure 12. Laboratory CBR corresponding to maximum dry unit weight according to sample location

5 Discussion

5.1 Overview

This study has shown that, in this case, subgrade compaction is likely the most important factor when trying to improve road strength. The comparisons of the laboratory and field test results showed that it might have been possible to improve the strength of the study road through increased compaction of the soil subgrade. The variability in the natural materials from the study road was observed through the soil classifications and particle size distributions. No significant relationships were found between the formation of ruts and the material properties.

The results of this case study should be considered when studying forest road strength and performance. The tests used for this study were designed to capture natural variability as well as trends among road construction practices, performance, and the engineering properties of the road building materials. Some of the data analyses did not show any patterns. It is possible that the sample size was too small to capture the significance of some relationships among the variables. Future studies of a similar nature could help to answer this question.

5.2 Interpretation of Results

5.2.1 Interpretation of In-situ Results

The Sand Cone test results showed a wide range of water contents present in the soil at time of construction. This wide range of values may be attributed to natural variability in soil moisture since the road was constructed during a wet period during the summer of 2004. If there is to be any standard or control over water content or density during construction of a new road, it is important to determine the natural variability in soil moisture before construction begins. In this case, there was no standard for target water content or density during construction. If an appropriate standard had been implemented and controlled, it is likely that a stronger road would have been the result.

The Clegg impact value (CIV) results were compared to the California bearing ratio (CBR) results to determine if any patterns could be seen between the observed road strength and the potential road strength measures. Correlation between these variables might help to identify a possible low cost alternative to costly laboratory testing. In this case it did not appear that there was a relationship between CIV with the 20-kg hammer and CBR at any of the compaction levels used in this study. It is possible that the natural variability in the soil was too great or the sample size was too small for a clear correlation to be observed. More research is needed in this area to determine if there is a clear relationship between CIV from the 20-kg hammer and soaked laboratory CBR.

The surface CIV's were used to examine the difference between the CIV's from the average of the right and left sides compared to the center CIV's (figure 6). This comparison illustrates the compaction that likely resulted from construction traffic on the road. It is likely that if the entire road had been compacted under controlled construction practices, the difference between the center CIV's and the sides would not have been observed. It is possible that some of the rutting observed on the road was "Mode 0" rutting resulting from road traffic as defined by Dawson (1997).

The results from the Kruskal-Wallis rank tests show that there was no statistically significant difference in subgrade or surface CIV between rutted and non-rutted segments. These results indicate that CIV was not a significant predictor of where ruts might occur in this case. However, generally the CIV for the subgrade were lower on road segments that showed rutting when compared to those without ruts (figure 13). It is possible that a larger sample size might reveal a statistically significant relationship between CIV and the formation of ruts. If this were the case, it might be possible to predict where ruts are likely to form and take action to prevent them. This practice would likely improve the environmental performance of forest roads while decreasing costs by providing a less expensive alternative to laboratory strength testing. It is also possible that the formation of ruts cannot be predicted with the methods used in this study. Future studies of a similar nature could help to answer this question.

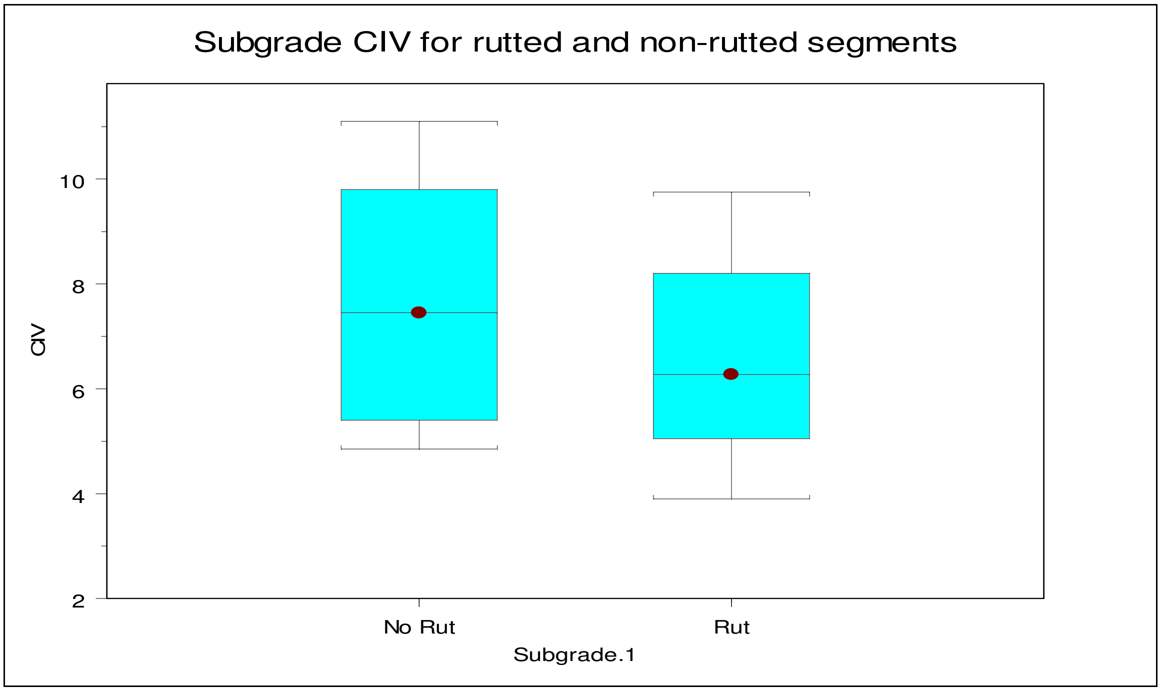

Figure 13. Subgrade Clegg impact values grouped by rutted vs. non-rutted road segments.

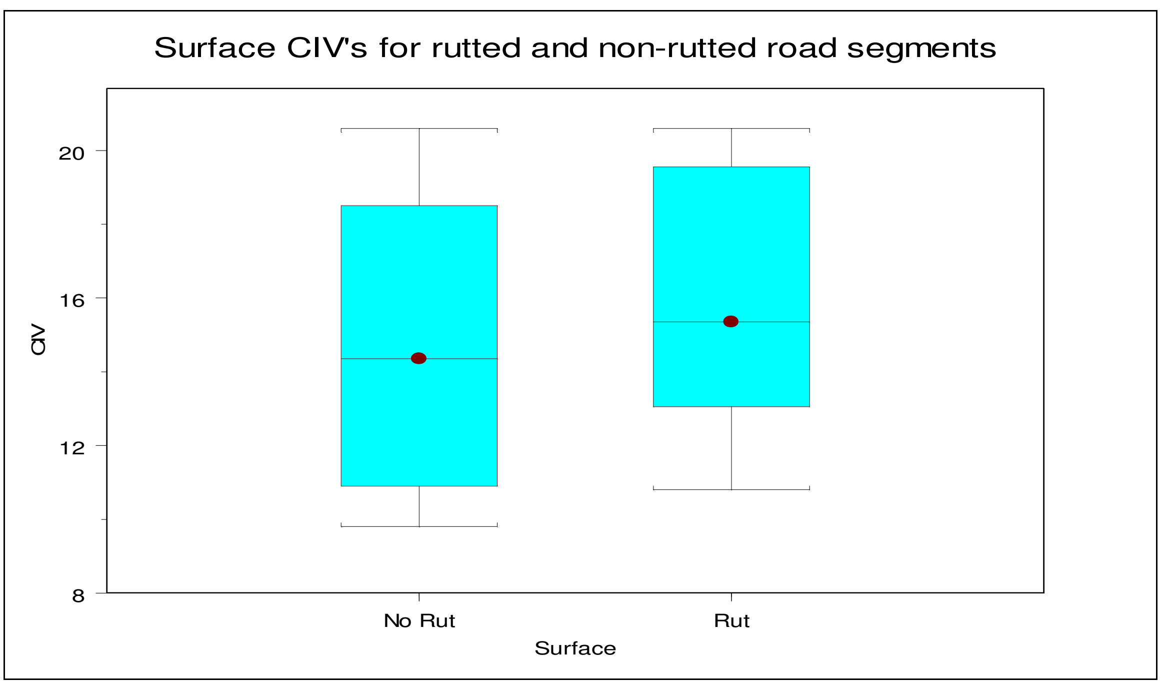

Figure 14. Surface Clegg impact values grouped by rutted vs. non-rutted road segments.

5.2.2 Interpretation of Laboratory Results

Laboratory classification through sieve analyses and Atterberg limits tests illustrated the small range of natural variability in the soils found on the study road. If it is possible to determine the variability of road building materials before construction, it might be possible to design the road based on the worst case scenario. This would assure low environmental costs; however, the financial costs may increase beyond acceptable levels. Land managers must make decisions on a case by case basis regarding the balance between environmental costs and financial costs.

Laboratory CBR tests generally showed standard text book relationships among water content, dry unit weight, and CBR at all three compaction levels; as compaction level increased, dry unit weight increased and optimum water content decreased. These tests indicated that although there was variation among soils, there is still a chance of developing a standard and controlling compaction of forest roads through moisture-density relationships. If the correct information is gathered at a reasonable sampling interval for a particular road, the design of that road may be improved. It might be possible to incorporate the appropriate moisture-density information into the road design to improve the overall strength of the road through controlled compaction. Future studies of a similar nature may help to determine the appropriate sampling density that will meet the needs for the design of stronger roads without an unacceptable increase in cost.

5.2.3 Interpretation of Data Snooping Results

5.2.3.1 Kruskal-Wallis

As expected, the Kruskal-Wallis rank test results show that the soil strength variables were different for different compaction levels. This information may allow land managers to determine the strength characteristics for a given soil with fewer laboratory tests. For instance, if the land manager were able to determine the optimum compactive energy required to balance the economic and environmental costs, then only that compactive energy would need to be tested in the laboratory. This might decrease the number of laboratory tests required by two-thirds. This assumption is based on the results from the Kruskal-Wallis rank tests that suggest that the soil strength variables are significantly different between compaction levels. The results of the laboratory Proctor and CBR tests would give the land manager the optimum water content for compaction at the given compactive energy and the resulting strength of that compacted soil. This practice may lead to stronger roads, with a relatively small increase in cost.

Five classes of soil were found in the samples for this study by the Unified Soil Classification System (USCS), however they were all very similar. The Kruskal-Wallis rank test results show that the soil strength variables were not significantly different by classification for a given compactive energy. In this case, higher priced Proctor compaction and CBR tests are required to determine the strength characteristics. It is possible that a statistically significant difference in the soil strength variables between classifications was not detected because the classifications were all very similar. It is also possible that the sample size for this study was too small to capture the variability of the soil and show the relationship between soil classification and soil strength characteristics if any exists. Another possibility is that there is in fact no relationship between soil classification and the soil strength variables measured. Future studies of a similar nature may help to answer this question.

If there truly is no difference in soil strength characteristics between different soil classifications then it might be possible to group several soil classifications together and treat them as one homogeneous soil. This would make designing and constructing a forest road simpler by requiring only one design for the entire road. This practice might reduce the number of expensive laboratory tests required to achieve stronger subgrades. For instance, in this case it might be possible that one road design including one target water content and target density, could be developed from a single 15-point CBR test rather than the 17, 15-point tests that were completed in this study. Assuming the design standard could be transferred to the ground with the proper construction control, it is likely that the entire length of the road would result in the constant bearing strength that was predetermined by the laboratory tests. This practice might significantly improve road strength with a relatively low increase in cost.

5.2.3.2 General soil Properties Compared to Soil Strength Properties

It appears from the simple linear regression results that in this case, soil strength properties are not greatly influenced by general soil properties including gradation and Atterberg limits. One significant relationship was found between plasticity index and the CBR value corresponding to the optimum water content at the modified Proctor level. At the high compaction energy used in the modified Proctor tests, increasing plasticity showed decreasing soil strength. It might be possible that highly compacted soils are more likely to be influenced by other soil properties, such as plasticity, because of the fewer air voids associated with the high compaction level (Smith and Smith, 1998). It might be possible that similar relationships among other variables exist but were not detected due to the small sample size. Future research in this area may help explain the relationship between general soil properties and soil strength characteristics.

It might also be possible that the single significant relationship observed between plasticity index and CBR was simply an anomaly. This significance might indicate a statistical type 1 error where the statistical test shows significance when there is actually none (The Animated Software Company, 2002). The probability of making this error is equal to the alpha level used for the test, which in this case was 0.05 (The Animated Software Company, 2002). It is possible that Atterberg limits are in fact correlated to soil strength properties but the sampling methods used for this study did not capture the appropriate amount of variability or range of values required to see additional significant relationships. However, in this case only one of 48 simple linear regressions showed a significant correlation between soil strength variables and general soil properties.

Assuming that soil strength characteristics are not influenced by general soil properties, higher priced Proctor compaction and CBR tests are required to determine the strength properties for this given soil. It is possible that the sample size for this study was too small to capture the variability of the soil and show the relationship between general soil properties and soil strength characteristics if any exists. It is also possible that there is in fact no relationship between these general soil properties and soil strength characteristics. Future studies of a similar nature may help to answer this question.

5.2.3.4 Clegg Impact Values Relating to Laboratory Test Results

The average of the subgrade Clegg impact values from the right and left sides of the road did not explain a significant amount of the variation in maximum dry unit weight or CBR. If the relationship between CIV and these soil strength characteristics were found to be significant, it might be possible to use the 20-kg Clegg hammer as a quality control tool during construction assuming a relationship could be developed between these variables. Obtaining CIV's is fast, easy and relatively inexpensive. Future studies of a similar nature may help to explain the correlation between these variables if one exists and how this correlation might help improve the construction of forest roads.

Thirty-four percent of the variation in the average of the subgrade CIV's from the right and left sides of the road was explained by the percent passing the No. 200 sieve. As percent passing the No. 200 sieve increased, CIV decreased. It appears that soils with more fine particles have less resistance to the Clegg impact hammer. It might be possible to use the Clegg impact hammer, an inexpensive and easy field test, to estimate the percent of fine particles in a soil without a laboratory sieve analysis. It is also possible that this relationship is unique to this study site and the sampling methods used. Future studies of a similar nature may help to better explain the significance of the correlation between these variables and how it might help improve the construction of forest roads.

5.2.3.5 Transformed Clegg Impact Values Relating to Laboratory CBR Results

In this case, the CIV's obtained with the 20-kg Clegg hammer are not significant in explaining any of the variation in CBR. However, a documented relationship exists between Clegg impact values (CIV's) measured with the 4.5-kg hammer and laboratory CBR values (Clegg, 1986),

$$CBR = (0.24 * CIV + 1)^2 \qquad [1]$$

This equation was developed for the 4.5-kg Clegg hammer as the result of data from both laboratory and in-situ test results of a wide variety of soils from Australia, New Zealand, and the United Kingdom (Clegg, 1986). This equation is not intended to be used with CIV data from the 20-kg Clegg hammer; however, it is possible that a similar relationship exists even though it was not observed in this study. For discussion purposes a short analysis was completed of the calculated CBR values using equation [1].

Two simple linear regressions were completed between the transformed CIV's using equation [1], and each of the CBR values of interest at each compaction level (maximum CBR and the CBR corresponding to maximum unit weight). These regressions follow the form y = a + bx and test if the slope, b, is statistically significantly different from zero using an $\alpha = 0.05$. The two groups of regression results can be seen on pages 58-59.

Test 1:

Independent variable = Transformed CIV

Dependent variable = Maximum CBR_i

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, $b \neq 0$

$F\text{-stat}_{10} = 0.16$, $df_{10} = 1$ and 15, $p\text{-value}_{10} = 0.69$

$F\text{-stat}_{25} = 3.82$, $df_{25} = 1$ and 15, $p\text{-value}_{25} = 0.07$

$F\text{-stat}_{56} = 0.35$, $df_{56} = 1$ and 15, $p\text{-value}_{56} = 0.56$

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that the transformed CIV's could not explain a statistically significant amount of the variability in the maximum CBR values at any compaction level (Appendix B.4 figure B-84 to figure B-86).

Test 2:

Independent variable = Transformed CIV

Dependent variable = CBR at Maximum Unit Weight_i

Where, i = 10, 25, and 56

Ho: Slope, b = 0

Ha: Slope, $b \neq 0$

F-stat $_{10}$ = 0, df $_{10}$ = 1 and 15, p-value $_{10}$ = 0.98

F-stat $_{25}$ = 3.27, df $_{25}$ = 1 and 15, p-value $_{25}$ = 0.09

F-stat $_{56}$ = 0.10, df $_{56}$ = 1 and 15, p-value $_{56}$ = 0.75

Result = Fail to reject Ho at all compaction levels

The results of the simple linear regression tests, using an $\alpha = 0.05$, fail to reject the null hypothesis for each compaction level. The conclusion from this test is that CIV could not explain a statistically significant amount of the variability in CBR at the maximum dry unit weight at any compaction level (Appendix B.4 figure B-87 to figure B-89).

The results from the two groups of regression tests completed on the transformed CIV's indicate that for this study, equation [1] does not help explain a statistically significant amount of the variation in the observed laboratory CBR values. It is possible however that an unknown relationship still exists between laboratory soaked CBR and CIV from the 20-kg Clegg hammer even though it was not detected in the data from this study. It is also possible that the difference in water content, dry unit weight, or compactive energy between CIV and CBR values used in this comparison influenced the results.

5.2.3.6 Transformed Clegg Impact Values Relating to Observed Rut locations

The results of the road survey showed that six of 18 road segments were rutted. In the spirit of data snooping, the transformed CIV's from equation [1] were compared to the laboratory CBR values at the standard Proctor compaction level for the stations where rutting was observed. This comparison is purely for discussion purposes since the equation used for the calculated CBR values was not intended for use with the 20-kg Clegg hammer that was used in this study.

Table 4 shows the locations where ruts were observed on the road, the observed maximum CBR values for the standard Proctor compaction level, and the transformed CIV's calculated from equation [1] at those sample points. Four of the six observed CBR values are higher than the transformed CIV's. If the transformed CIV and its comparison to the observed CBR value is in fact a meaningful comparison, then it appears that the potential strength of the soil was not achieved in the field. It might be possible to improve construction practices to achieve the full potential of the soil and help to prevent ruts from forming on forest roads.

Table 3. Observed laboratory CBR values and transformed CIV's for stations where rutting was observed.

Station where ruts were observed	Road location where ruts were observed (ft)	Laboratory maximum CBR from standard Proctor level	$CIV_{transformed} = (0.24 * CIV + 1)^2$
TM1	0	4.40	9.69
TM3	600	5.18	11.23
TM5	1200	8.60	7.51
TM8	2100	5.88	5.18
TM9	2400	12.64	3.78
TM14	3900	11.24	4.94

5.3 Actual vs. Optimal Road Conditions

5.3.1 Field vs. Laboratory Results

The results from figures 4, 5, 9, and 10 show that the potential strength of the soil subgrade was not achieved at the time of construction. As mentioned before, the wide range in values of water content and dry unit weight obtained from the Sand Cone results indicate that there was no standard and little control over these factors during construction of the subgrade. The CBR results from the standard Proctor compaction level show the potential bearing strength of the soil under controlled conditions. On average, the relative density achieved in the field compared to the standard Proctor laboratory results was only 76%. Many earthwork specifications require field dry unit weight to be at least 90% to 95% of standard Proctor laboratory results (Das, 2002). From these results it appears that the construction of the soil subgrade of the study road could have been improved through increased control of water content or compaction during construction.

Future studies may reveal what significance, if any, exists regarding spatial correlation of soil strength characteristics. It might be possible that similar soil strength characteristics can be grouped together in space. A separate road design could be created and implemented for each group within one road segment. This practice might help improve road design and performance while keeping costs relatively low by preventing over-design of the entire road segment.

5.3.2 Theoretical Economic Analysis

A stronger subgrade on a forest road might lead to a decrease in the instances of rutting. Some theoretical economic analysis was completed using the rut depth equation developed by the United States Army Corps of Engineering Waterways Experiment Station and used by the U.S. Forest Service (USFS, 1996).

$$\text{Rut Depth} = 0.1741 * ((8.64^{0.4704} * 80^{0.5695} * \text{ESWL's}^{0.2476}) / ((\text{LOG(surface thickness)})^{2.002} * \text{Surface CBR}^{0.9335} * \text{Subgrade CBR}^{0.2848})) \quad [2]$$

The results of the rut depth analysis show that if the subgrade CBR value could be increased from eight to 23, the land manager has the potential of saving $4183 in maintenance costs if rutting was limited to 1.5 inches (in). A CBR of eight corresponds to 95% of the average maximum CBR values from the laboratory results of this study at the standard Proctor level. A CBR of 23 corresponds to 95% of the average maximum CBR values from the laboratory results of this study at the middle compaction level. The cost of the extra compaction needed to achieve a subgrade CBR of 23 would be $999. The total savings to the land manager would be $3184. The assumptions for this analysis can be seen in Appendix C.

The results of the rut depth analysis using equation [2] show the effect of subgrade strength on the overall degree of rutting seen on the theoretical road. If the subgrade had a CBR of eight the resulting rut depth would be 1.8 in. If the subgrade CBR could be increased to 23 with increased compaction, the resulting rut depth would be 0.47 in. If the allowable rut depth was 1.5 in, the road with the weaker subgrade would have to be maintained twice in the hauling season. If the land manager chose to maintain the road only once then the road would have ruts at the end of the hauling season. As mentioned before, a rutted road can produce as much as seven times the sediment of a non-rutted road (Reid and Dunne, 1984). If the road with the weaker subgrade CBR was not maintained it would most likely produce more sediment than a similar road without ruts.

Decreases in rutting depth would lead to increased environmental performance and decreased maintenance costs. The road with a theoretical subgrade CBR value of 23 had only 0.47 in of rutting at the end of the hauling season. This cost of maintenance for this road was calculated to be $1371 and after maintenance the rut free condition of the road would decrease the amount of sediment that road would produce.

5.4 Answering the Study Objectives

This study of the one-mile road segment in the Oregon Coast Range showed that in this case, forest road construction may have been improved through increased control of soil water content and compaction. The variability was observed in the road building materials through both field and laboratory observations. The potential strength of the road building materials observed in the laboratory was greater than the strength of the road observed in the field. The formation of ruts on the road could not be correlated to any of the variables tested.

Using linear regression and the Kruskal-Wallis rank test the data were analyzed for possible correlations. Most relationships between general soil properties (sieve analysis, Atterberg limits, and classification) and soil strength characteristics (optimum water content, maximum dry unit weight, and CBR) were not found to be statistically significant. It is possible that the sample size was too small to detect a difference between these properties. However, the lack of correlation from numerous comparisons indicates that for this site, soil strength is not influenced by other soil properties. Therefore, for this study, compaction of the soil subgrade is likely the most important aspect in providing strength to the road.

Using the Kruskal-Wallis rank test the CIV data were analyzed for possible correlations with the formation of ruts on the study road. Generally, rutted road segments had lower subgrade CIV's than non-rutted road segments however no significant difference was found. It is possible that the sample size was too small to allow significant relationships to be seen between the formation of ruts and subgrade CIV. For this study, the lack of significance of the statistical analysis indicates that the formation of ruts cannot be explained by the variables tested.

5.5 Limitations and Recommendations

There are limitations associated with all scientific studies. The results of this case study do not represent roads other than the one that was analyzed. This study can be used as a guide for planning subsequent studies. The results of this case study should also be examined by those concerned with road construction quality, road performance, and road testing methods.

According to the literature reviewed for this project there have been no studies similar to this one. Absent a model to follow, the data analysis for this study proved to be quite difficult. Exploration of data is an appropriate practice for searching for trends in studies that are the first of their kind. It is possible that there are relationships in this data that were not uncovered in the data snooping expedition. The data will continue to be analyzed and compared to future data sets in an ongoing search for correlations.

From the results of this case study it appears that compaction is likely the most important aspect in improving road strength. Based on this study, land managers and road contractors should consider ways to develop and implement standards for target water content and density during forest road construction projects. The optimum breakeven point between increases in cost and decreases in negative environmental effects through increased road strength should also be determined. Road design incorporating site specific, soil strength characteristics should increase overall road performance by bringing in-situ material strength closer to its ultimate potential.

6 Conclusion

The results from this case study of a road segment on the Oregon Coast Range show many interesting things about road construction practices and road building materials. Field testing on the road during construction measured density and water content of the soil subgrade as well as impact values for the subgrade and surface. The incidence of ruts was observed after timber was hauled on the road. Laboratory testing on the road materials measured general soil characteristics including classification. Soil strength was measured in the laboratory with the California bearing ratio (CBR) 15-point testing series.

As expected, the results of this case study show that compaction of the soil subgrade was likely the most important aspect in providing strength to the road and potential improvement in design and construction. Other soil properties, such as classification, were not found to significantly explain anything about the strength of the soil.

A wide range of results for each test used in this study show the natural variability that exists on this road site. It is possible that relationships between variables were not discovered in this study because of the limited sample size. Future studies of a similar nature may help to answer this question.

Results from the comparisons between field and laboratory tests suggest that the potential strength of the soil was not achieved in the field at the time of construction. It might be possible that the full potential of road building materials can be obtained through increased control of soil water content and compaction during construction.

The performance of the road was measured by the occurrence of ruts that were observed. No correlations can be drawn between the variables tested in this study and the formation of ruts.

This study is the first of its kind and has uncovered some important elements to examine when studying forest roads. Compaction of soil subgrades is very important as is finding the optimum conditions for compaction. These elements are essential in the design and construction of forest roads to ensure that the road will withstand traffic and resist deformation.

The significance of this study will not be entirely determined until more research has been done. For now, this study can be used as a starting point for subsequent research on road strength and performance. Future studies may show similar results; that compaction of soil subgrade is the most important aspect in providing strength to forest roads.

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ASTM D 422-63 (1998) Standard Test Method for Particle-Size Analysis of Soils

ASTM D 698-00 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3)

ASTM D 1556-00 Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method

ASTM D 1557-00 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3)

ASTM D 1883-99 Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils

ASTM D 2216-98 Standard Test Method for Laboratory Determination of Water Content of Soil and Rock by Mass

ASTM D 2487-00 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

ASTM D 2922-01 Standard Test Method for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)

ASTM D 3017-01 Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)

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APPENDICES

Appendix A. CBR Data

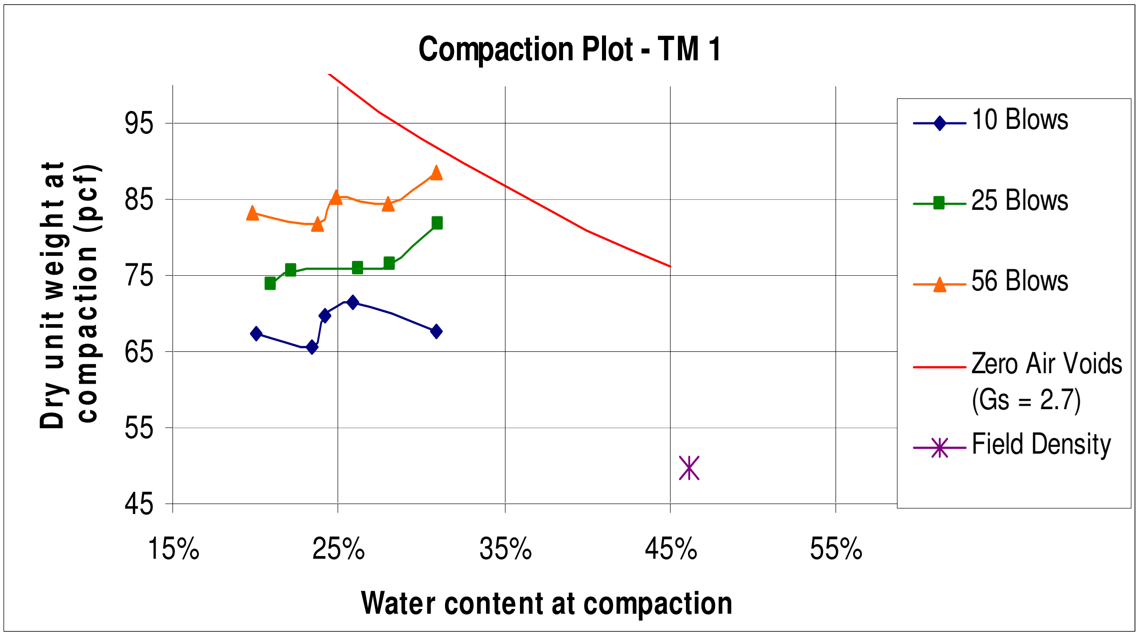

Figure A - 1. Compaction plot for sample TM 1 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

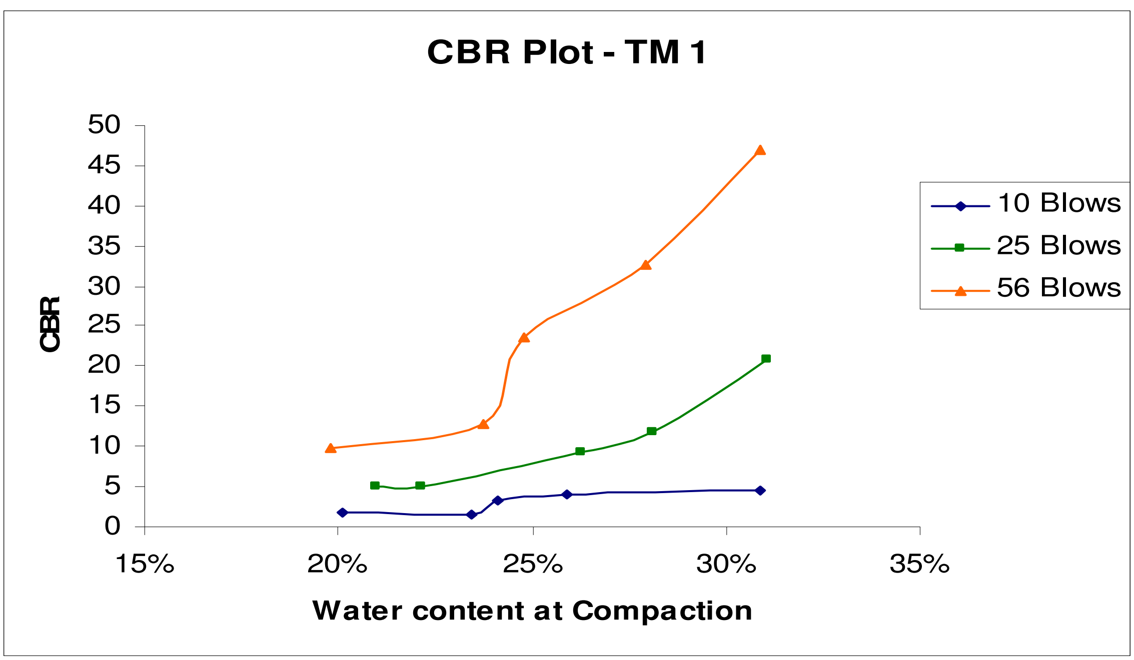

Figure A - 2. CBR plot for sample TM 1 showing water content at compaction and observed CBR value for three compaction levels.

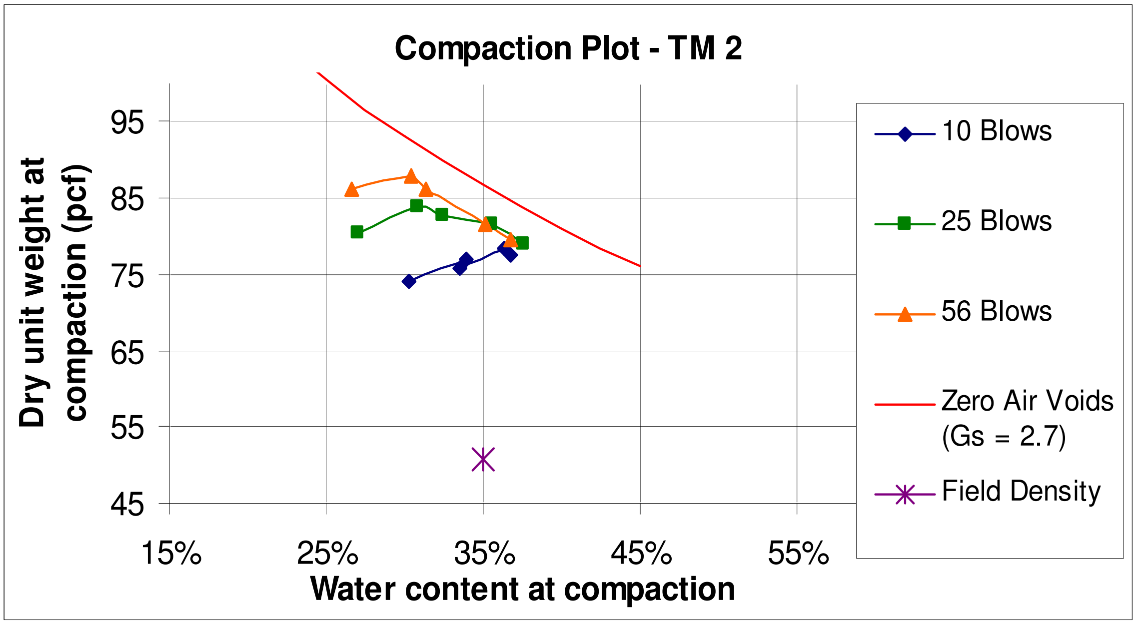

Figure A - 3. Compaction plot for sample TM 2 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

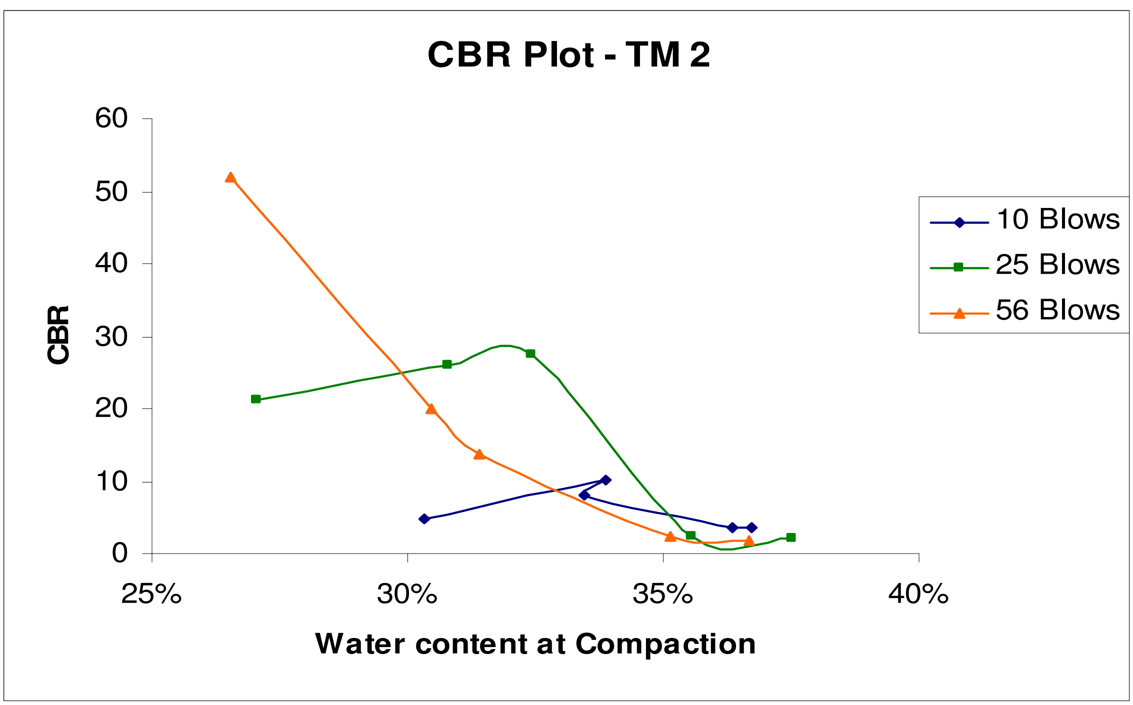

Figure A - 4. CBR plot for sample TM 2 showing water content at compaction and observed CBR value for three compaction levels.

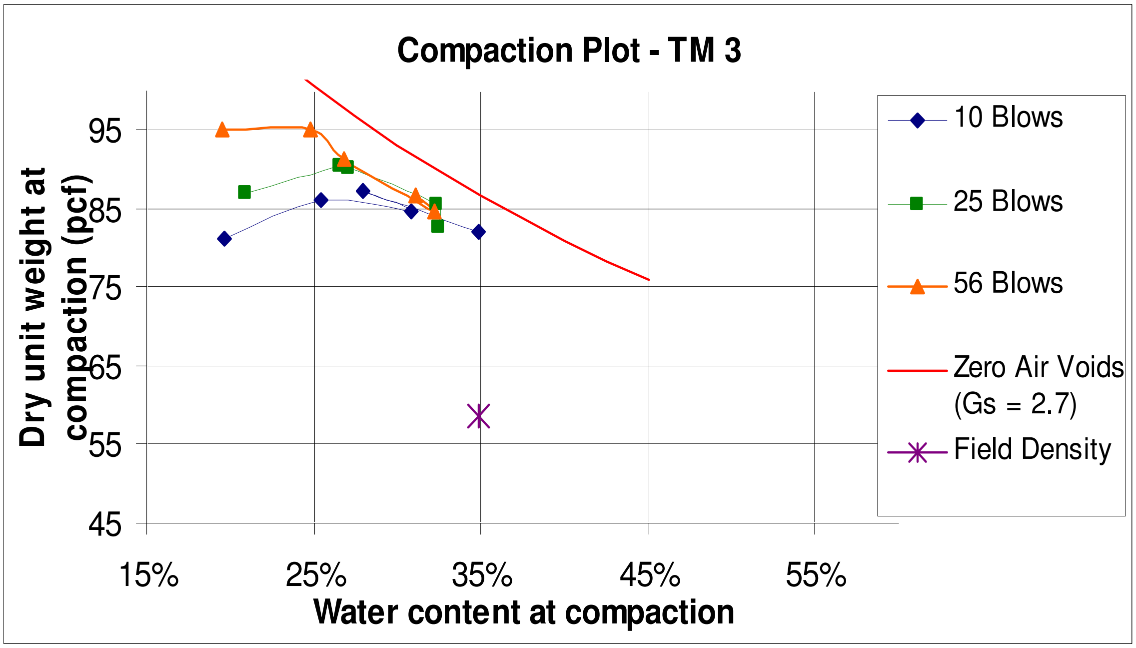

Figure A - 5. Compaction plot for sample TM 3 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

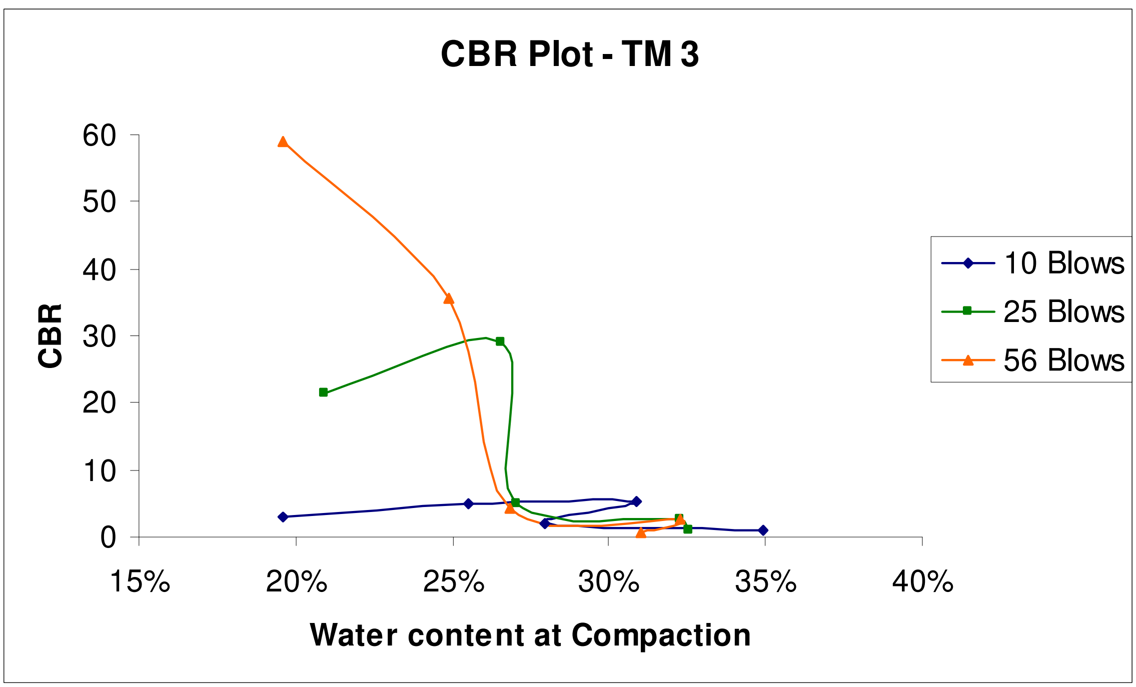

Figure A - 6. CBR plot for sample TM 3 showing water content at compaction and observed CBR value for three compaction levels.

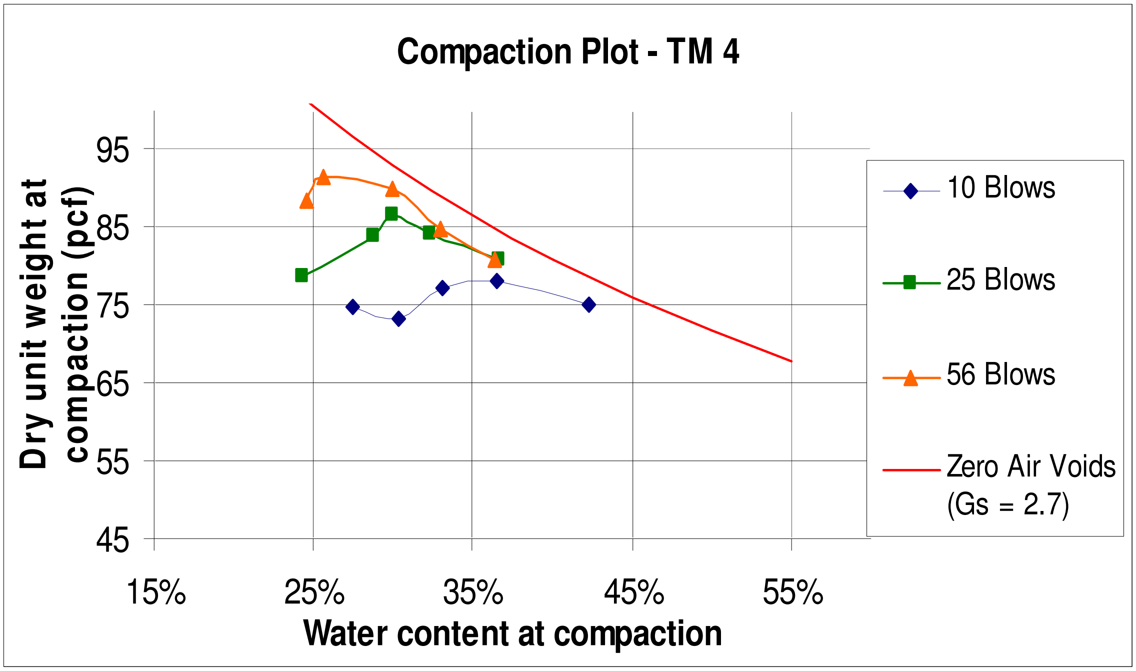

Figure A - 7. Compaction plot for sample TM 4 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

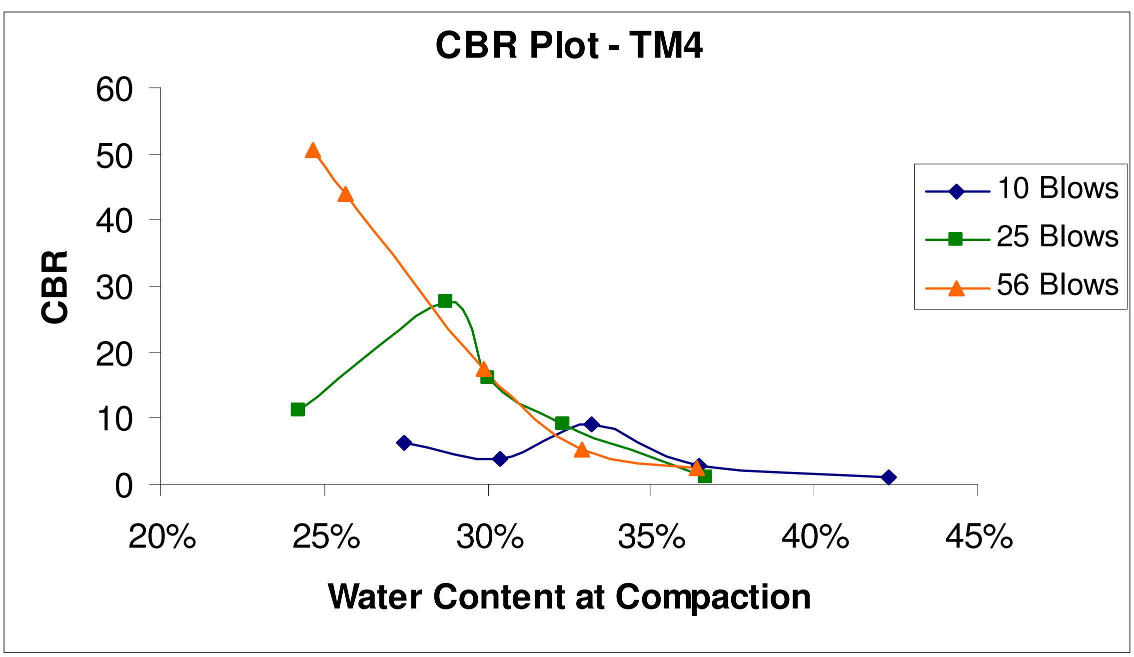

Figure A - 8. CBR plot for sample TM 4 showing water content at compaction and observed CBR value for three compaction levels.

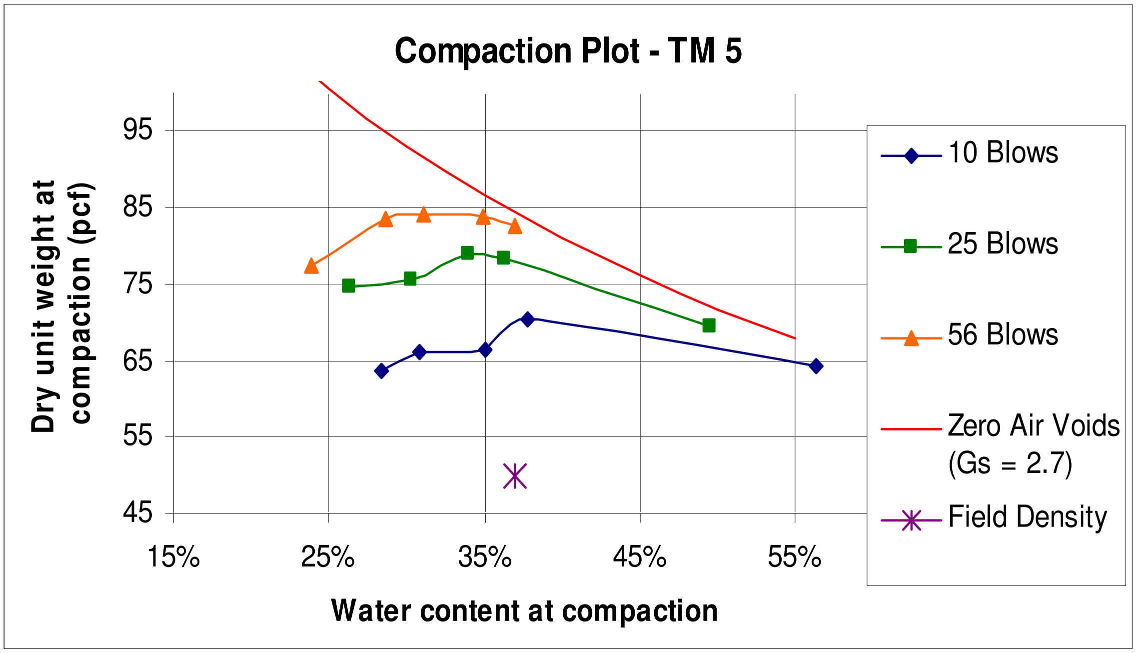

Figure A - 9. Compaction plot for sample TM 5 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

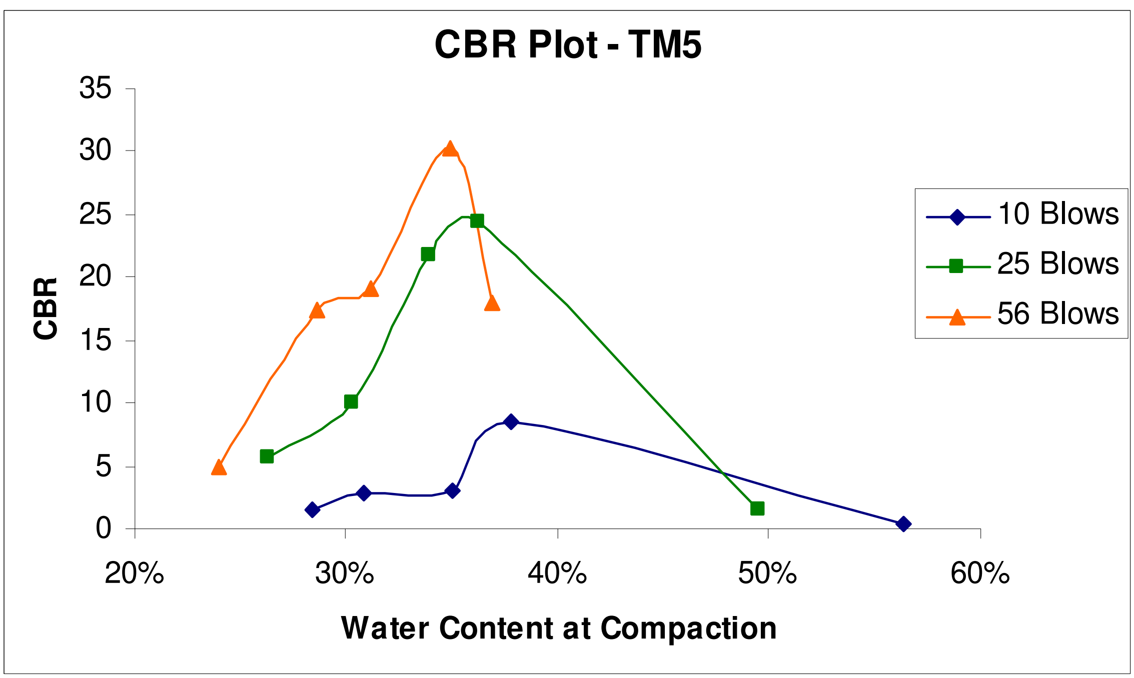

Figure A - 10. CBR plot for sample TM 5 showing water content at compaction and observed CBR value for three compaction levels.

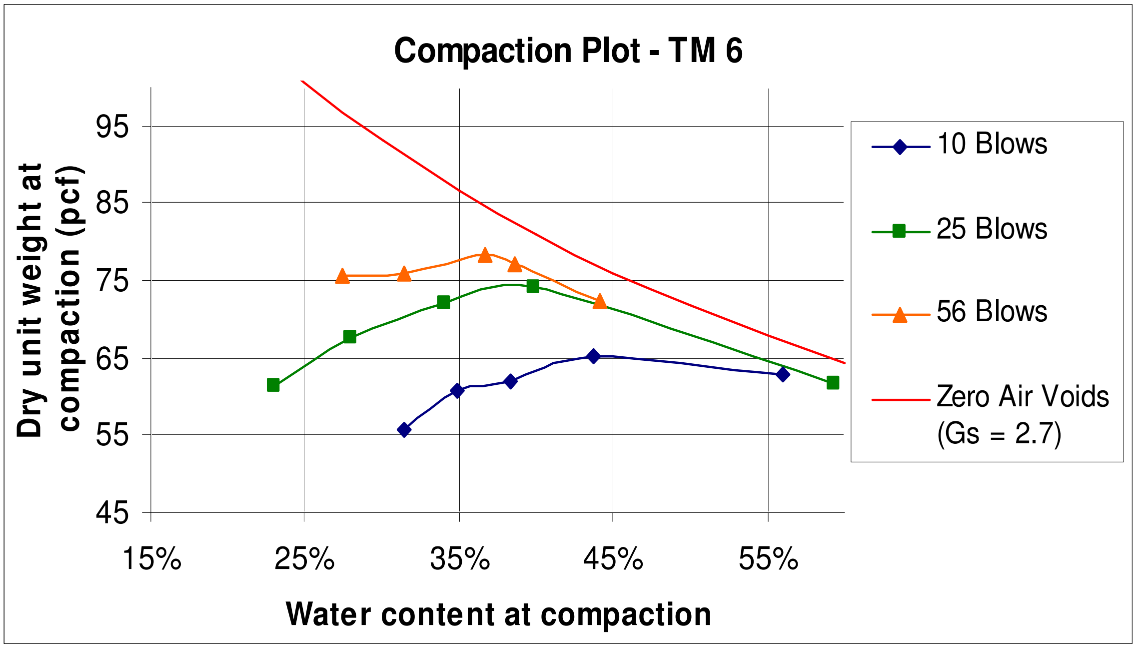

Figure A - 11. Compaction plot for sample TM 6 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

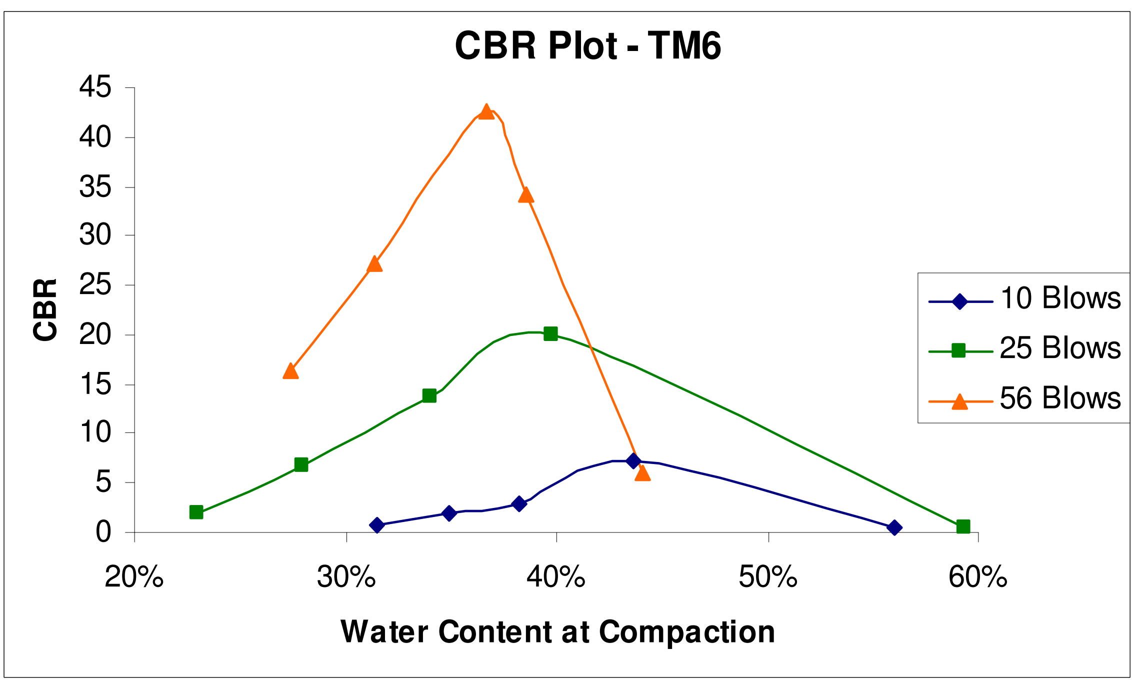

Figure A - 12. CBR plot for sample TM 6 showing water content at compaction and observed CBR value for three compaction levels.

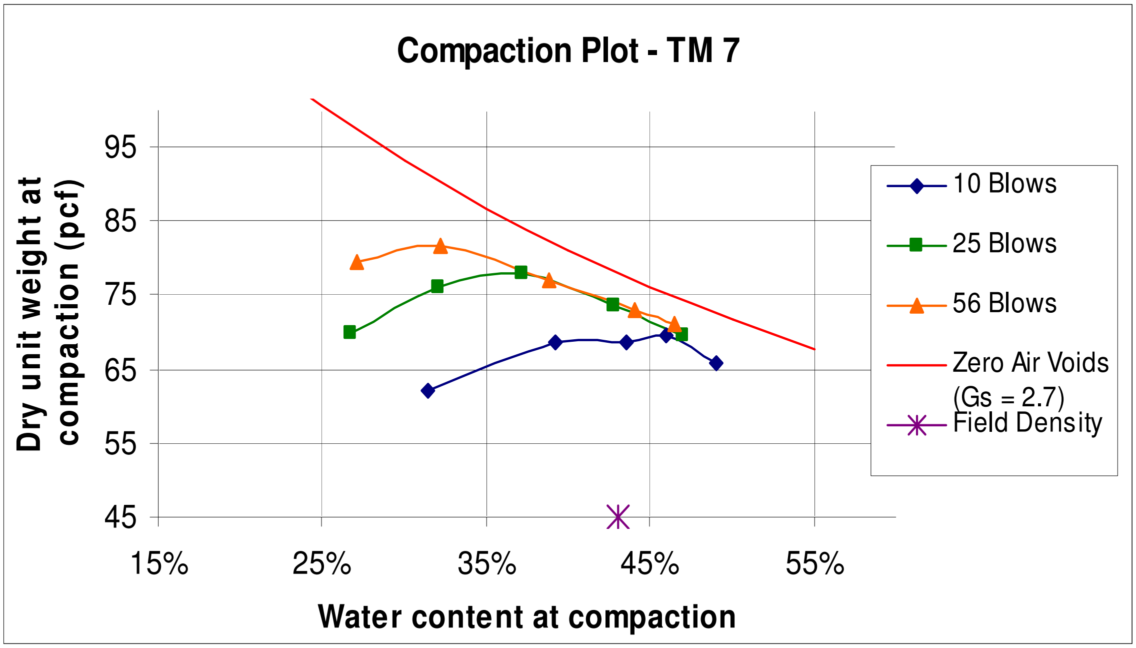

Figure A - 13. Compaction plot for sample TM 7 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

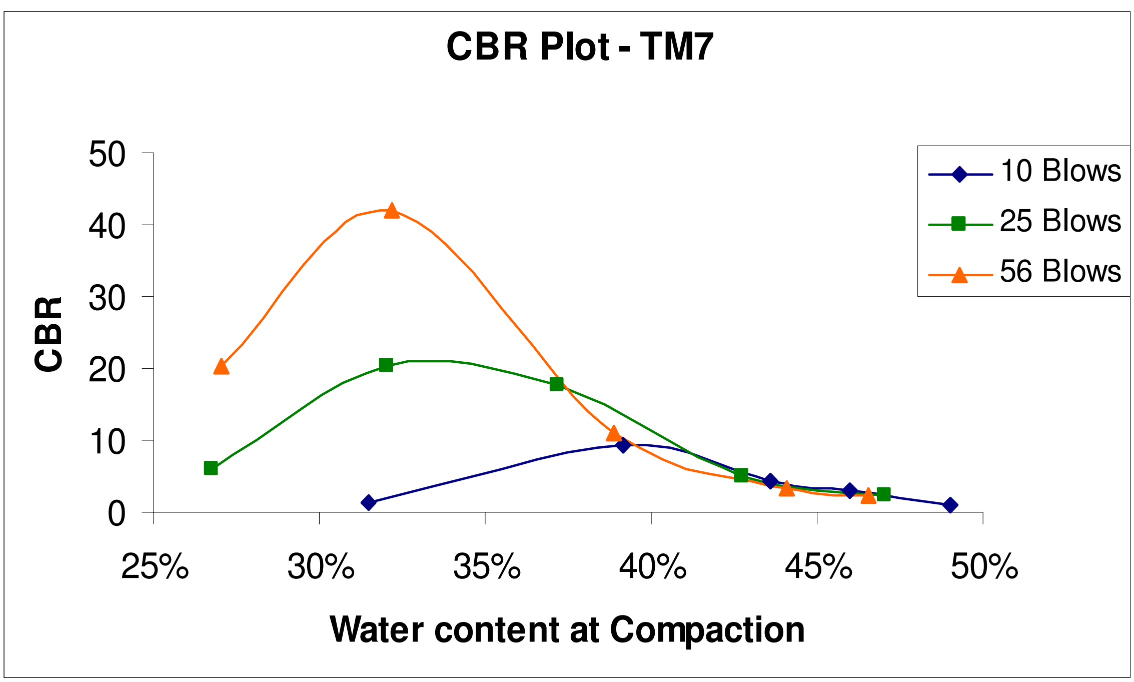

Figure A - 14. CBR plot for sample TM 7 showing water content at compaction and observed CBR value for three compaction levels.

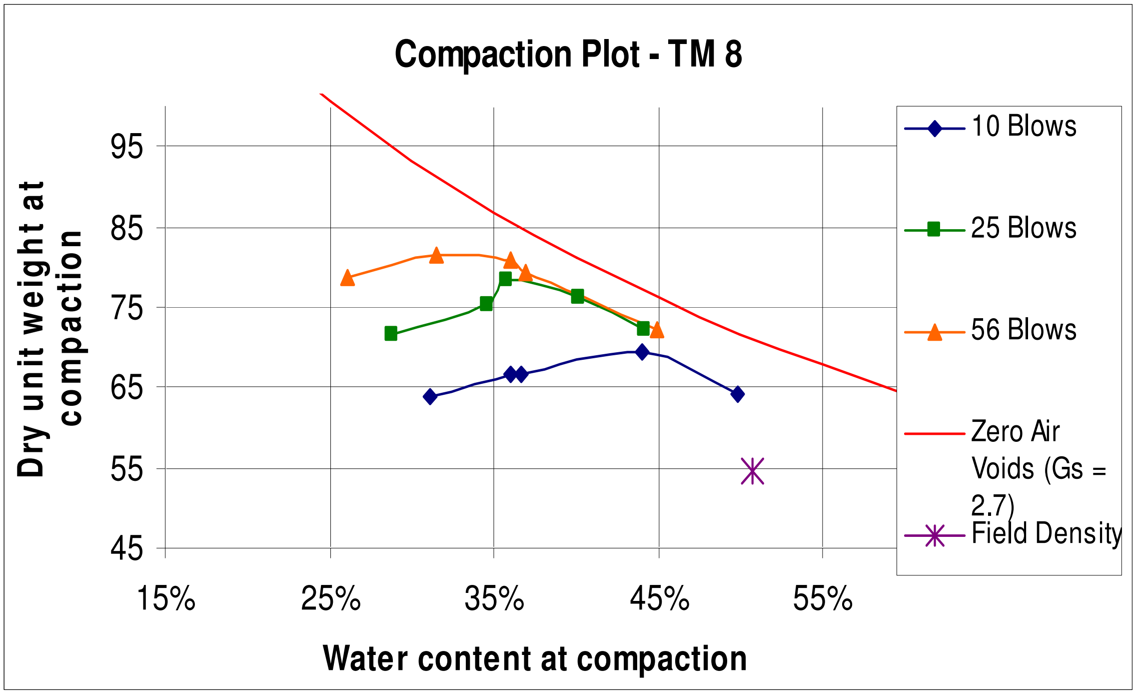

Figure A - 15. Compaction plot for sample TM 8 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

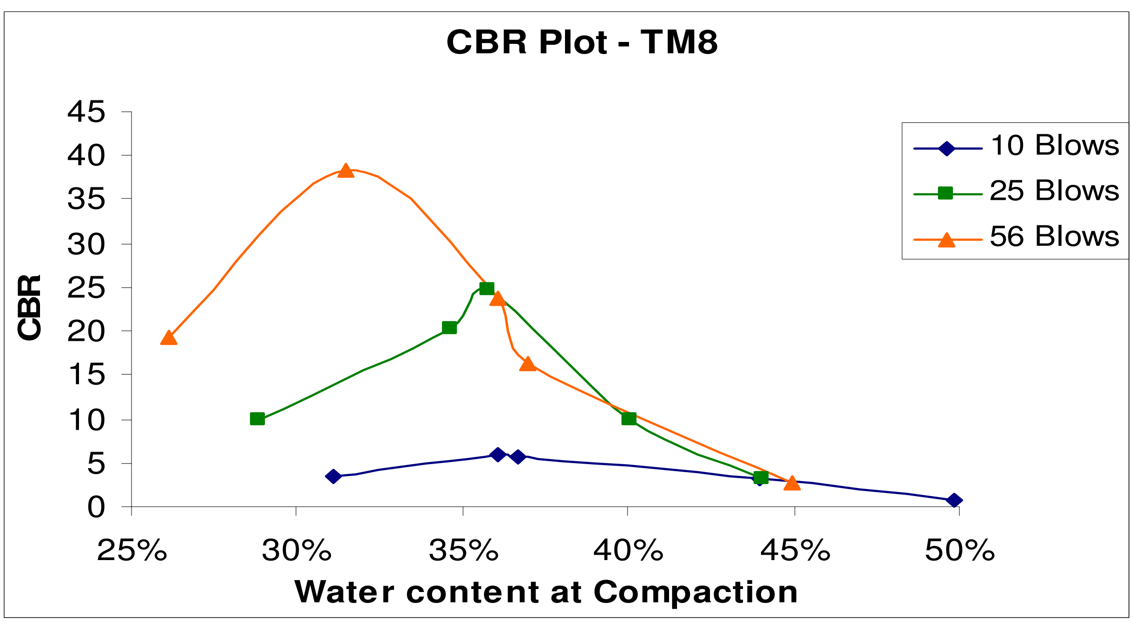

Figure A - 16. CBR plot for sample TM 8 showing water content at compaction and observed CBR value for three compaction levels.

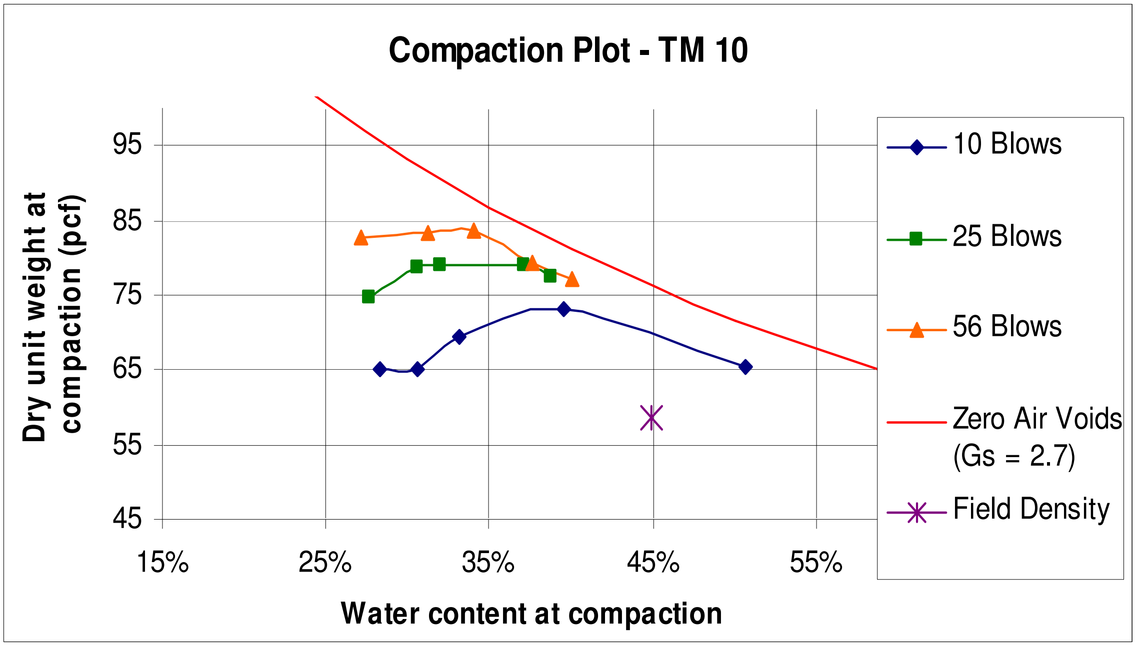

Figure A - 17. Compaction plot for sample TM 10 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

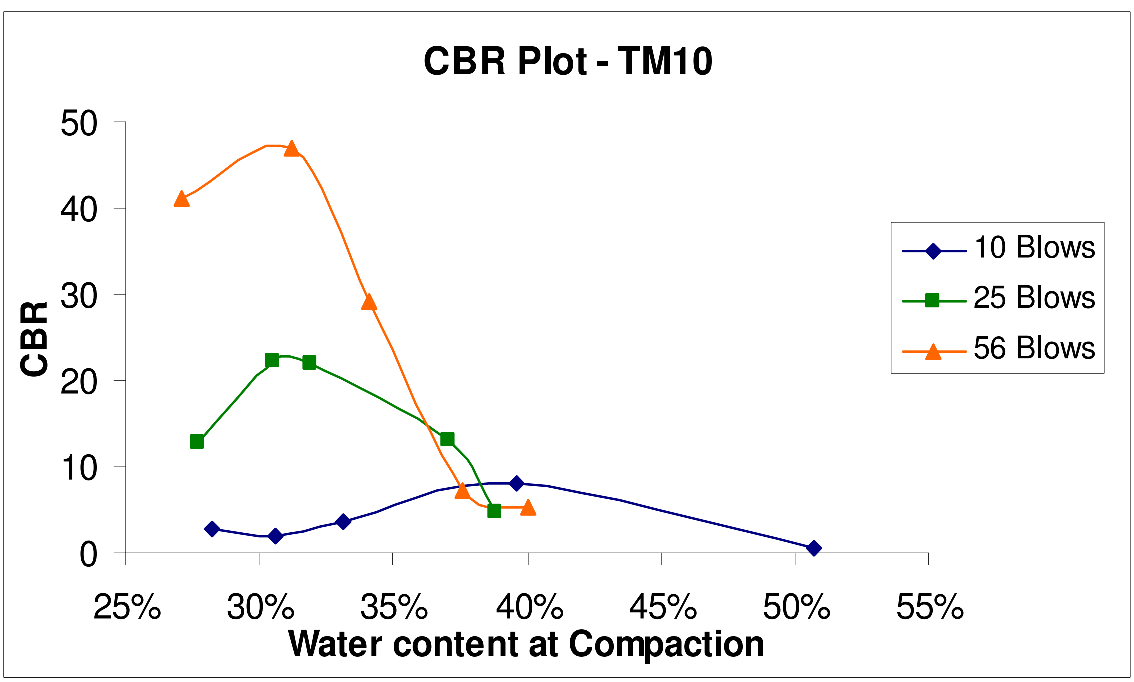

Figure A - 18. CBR plot for sample TM 10 showing water content at compaction and observed CBR value for three compaction levels.

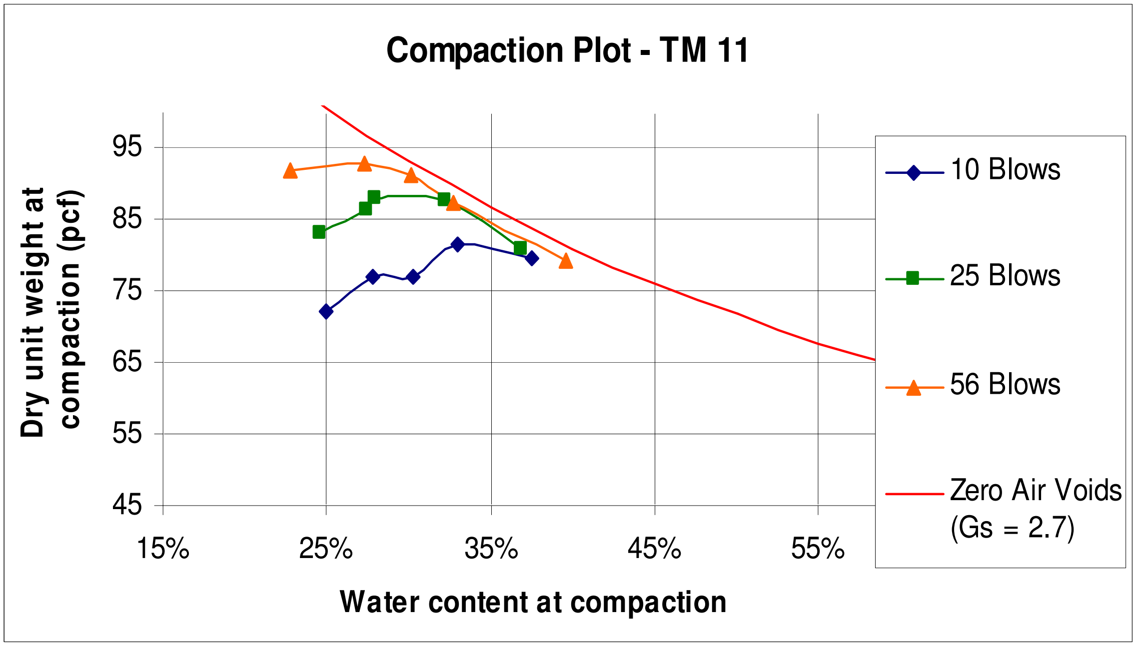

Figure A - 19. Compaction plot for sample TM 11 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

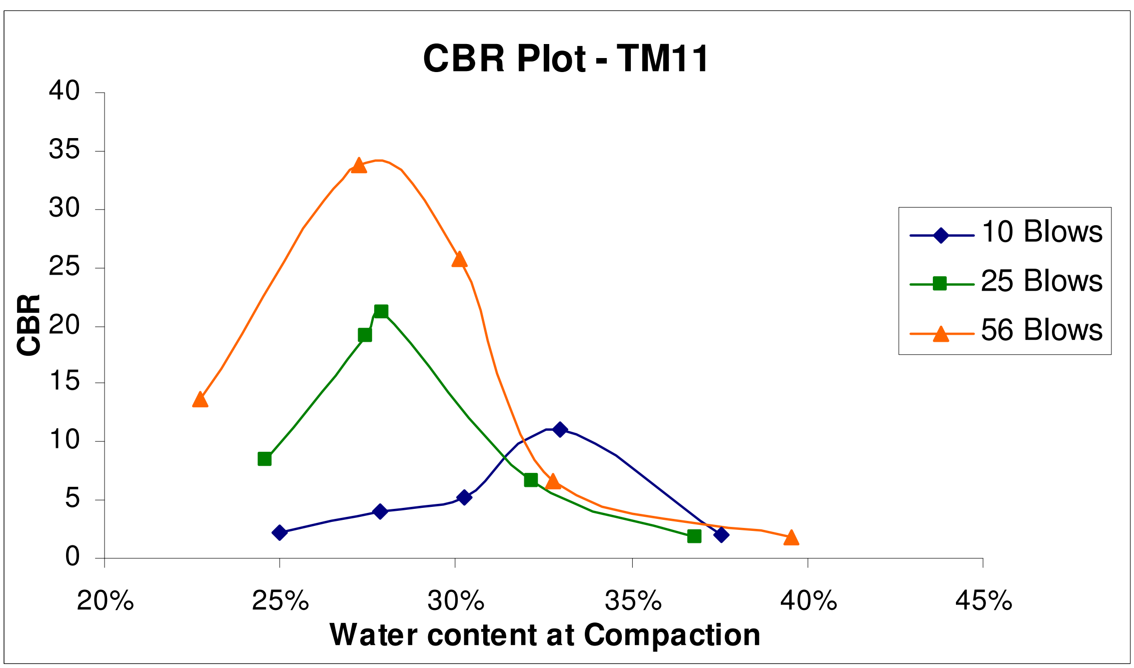

Figure A - 20. CBR plot for sample TM 11 showing water content at compaction and observed CBR value for three compaction levels.

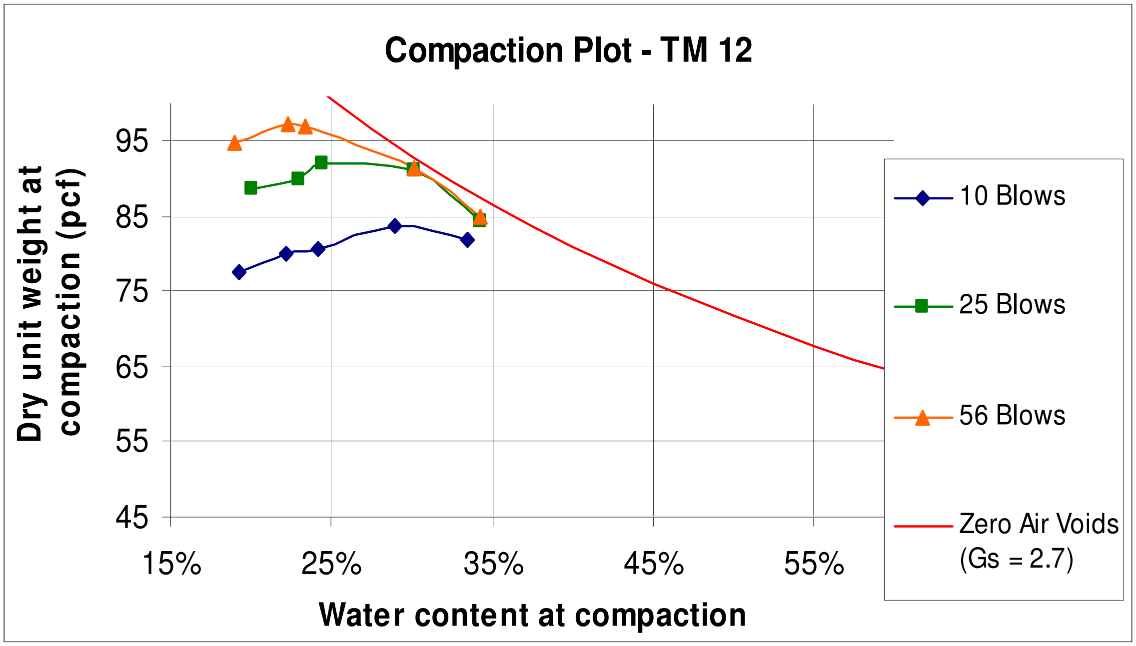

Figure A - 21. Compaction plot for sample TM 12 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

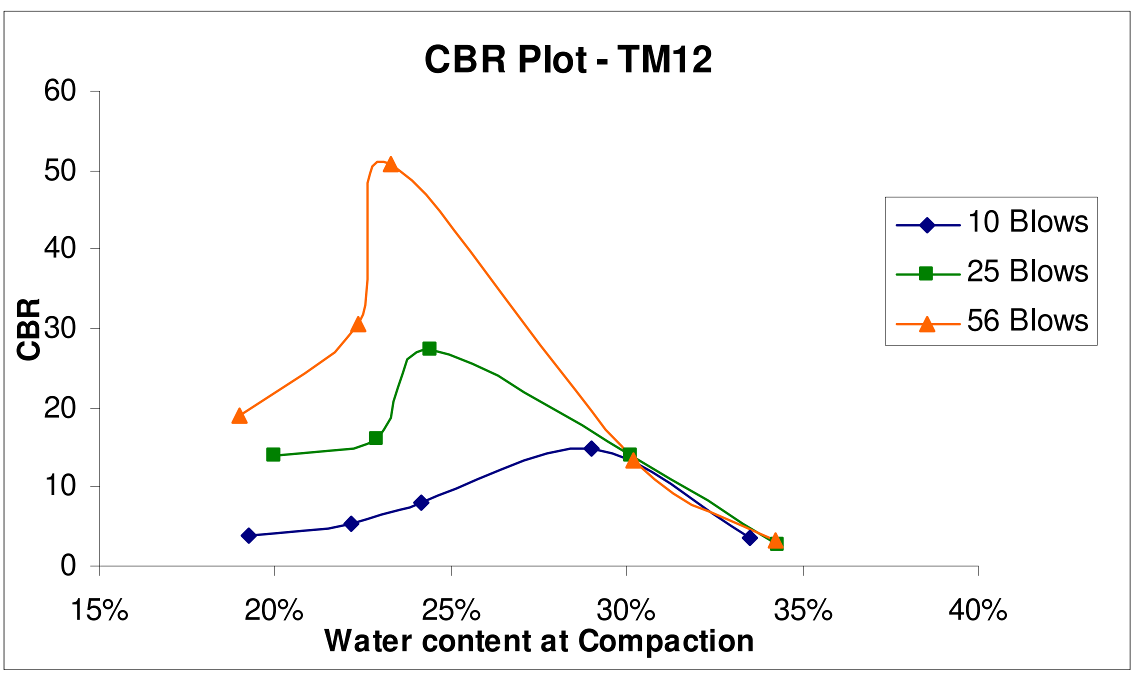

Figure A - 22. CBR plot for sample TM 12 showing water content at compaction and observed CBR value for three compaction levels.

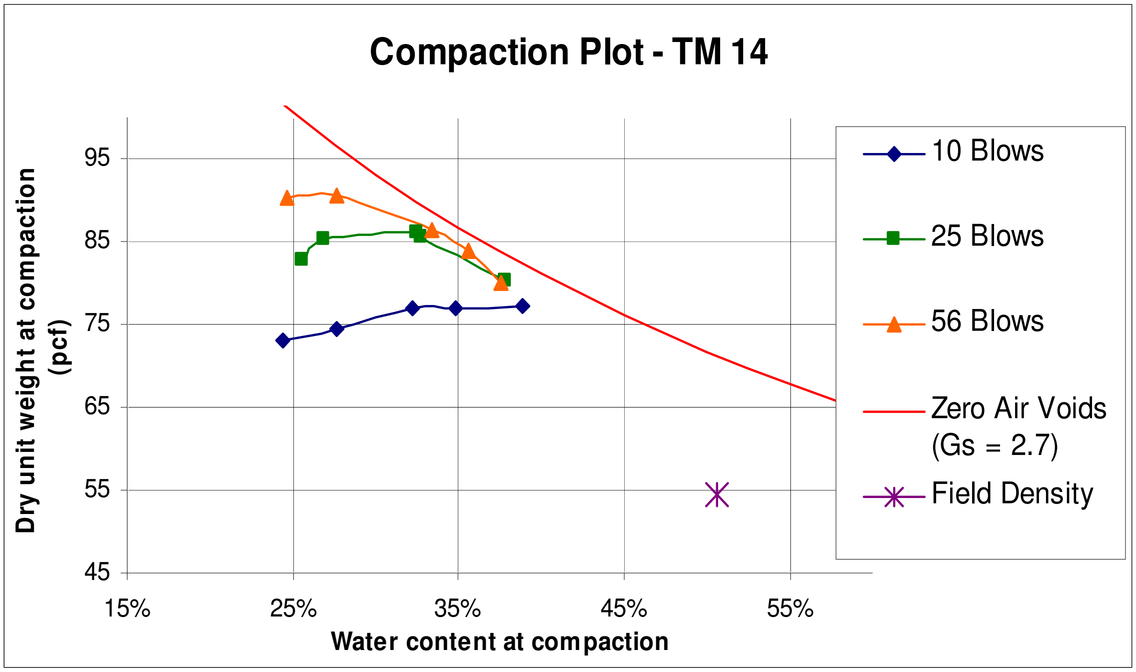

Figure A - 23. Compaction plot for sample TM 14 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

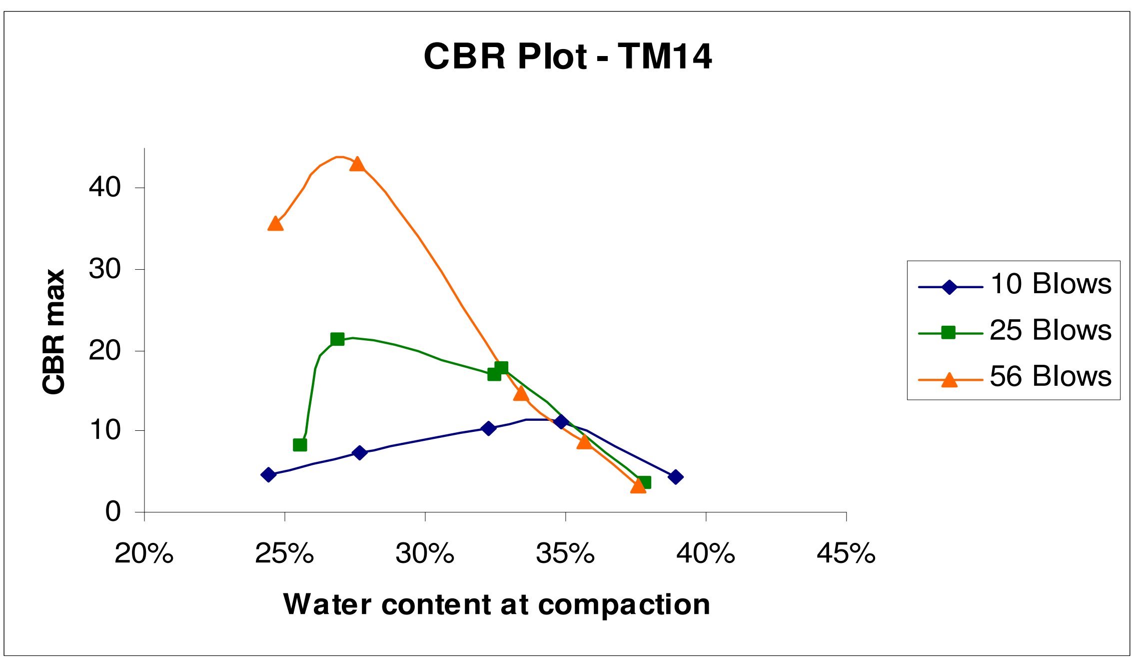

Figure A - 24. CBR plot for sample TM 14 showing water content at compaction and observed CBR value for three compaction levels.

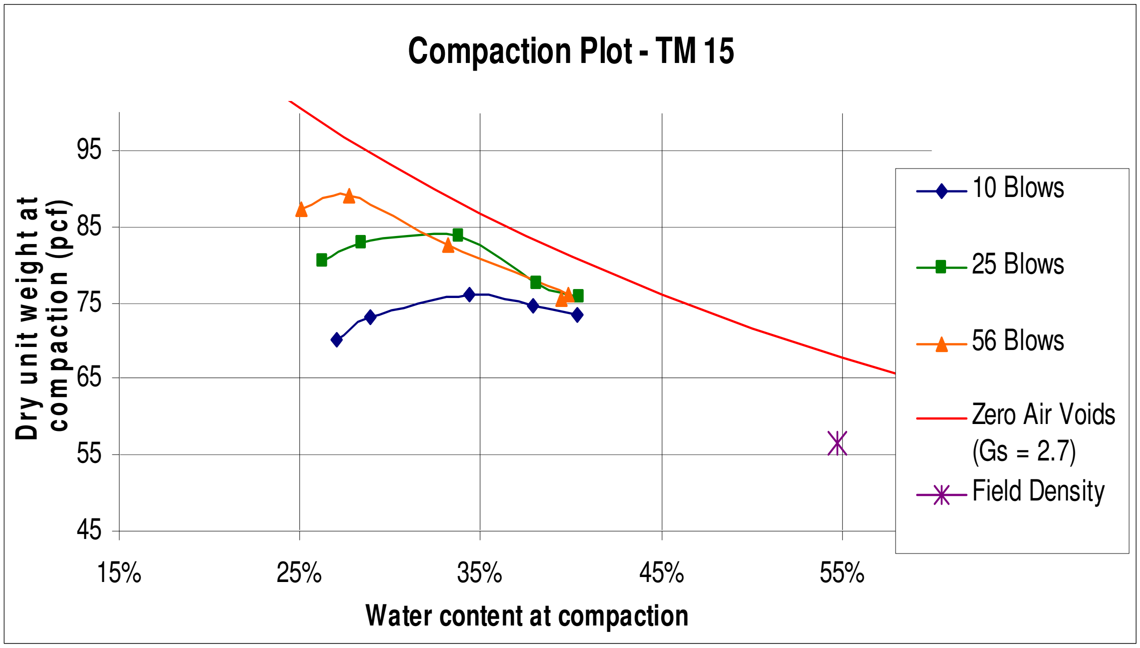

Figure A - 25. Compaction plot for sample TM 15 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

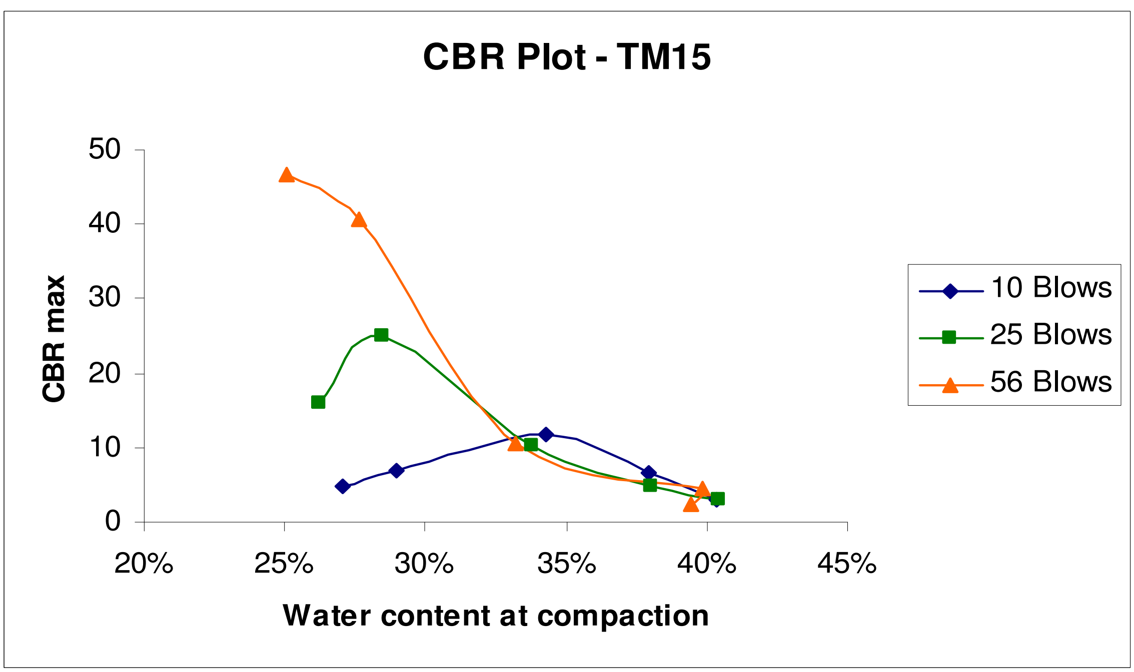

Figure A - 26. CBR plot for sample TM 15 showing water content at compaction and observed CBR value for three compaction levels.

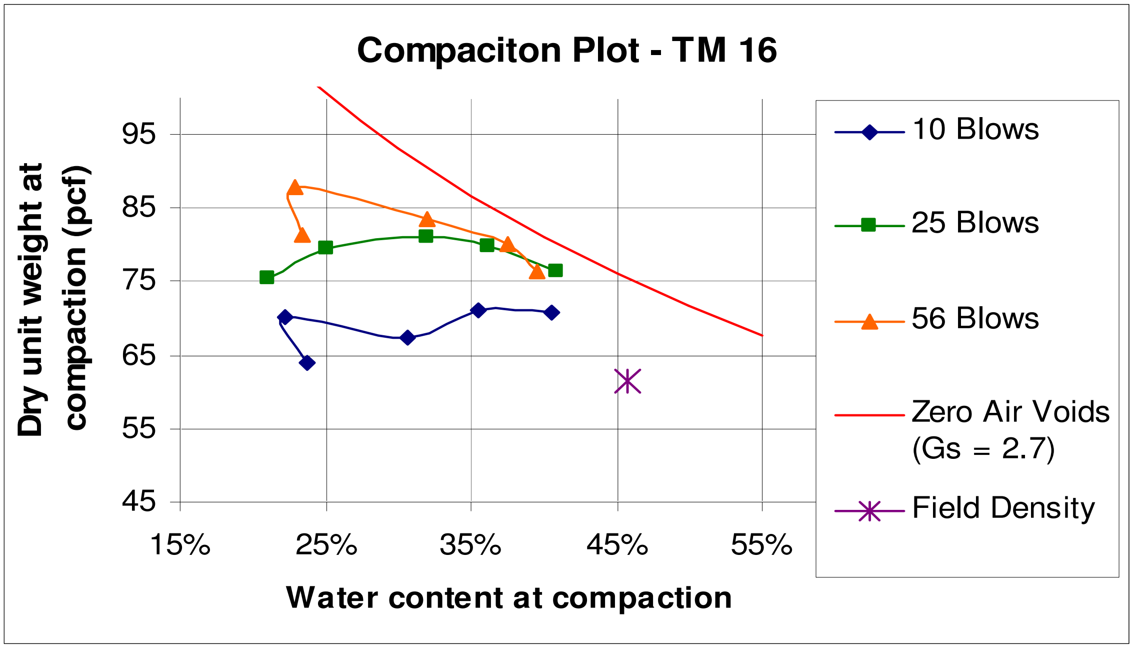

Figure A - 27. Compaction plot for sample TM 16 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

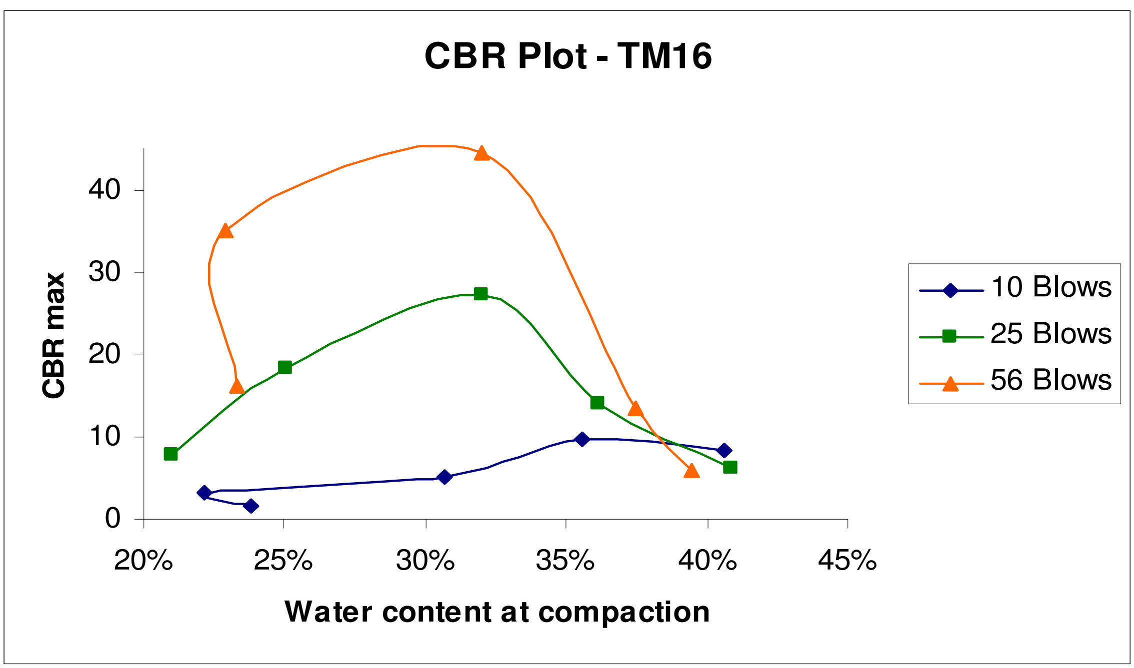

Figure A - 28. CBR plot for sample TM 16 showing water content at compaction and observed CBR value for three compaction levels.

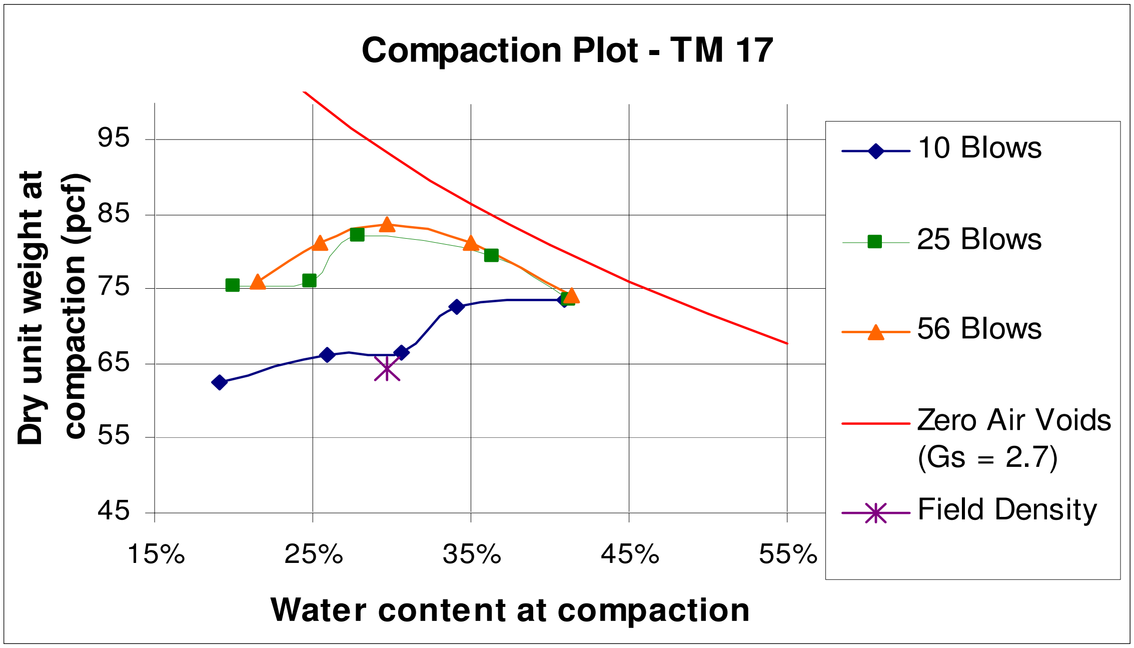

Figure A - 29. Compaction plot for sample TM 17 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

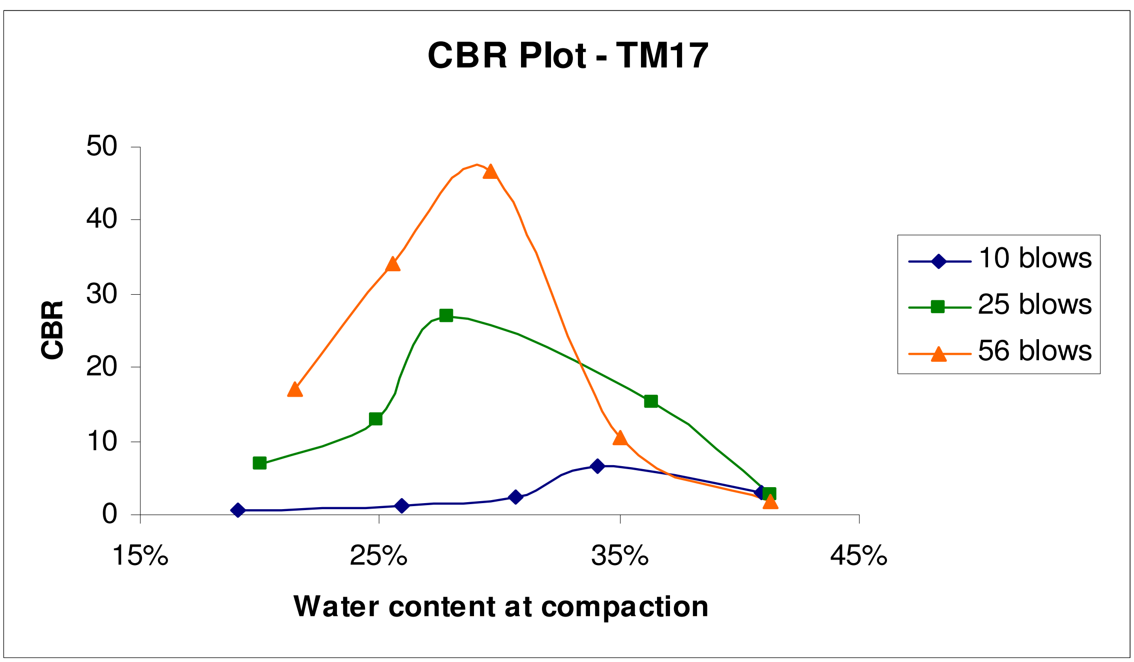

Figure A - 30. CBR plot for sample TM 17 showing water content at compaction and observed CBR value for three compaction levels.

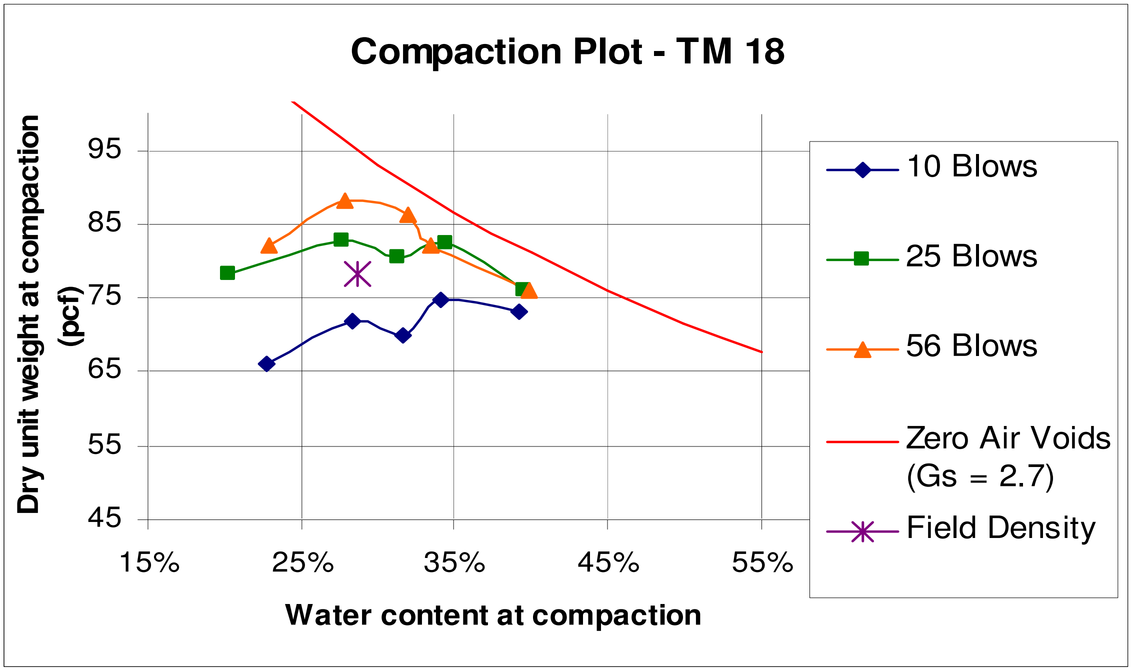

Figure A - 31. Compaction plot for sample TM 18 showing compaction water content and resulting dry unit weight for three compaction levels and the zero air voids curve using a specific gravity of 2.7.

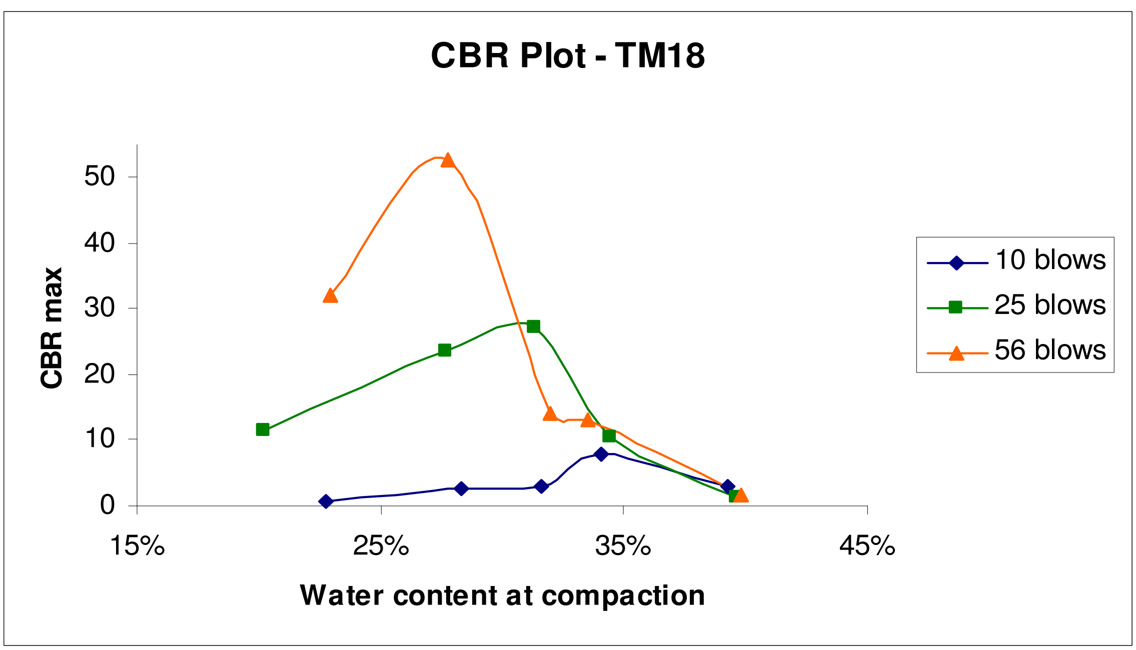

Figure A - 32. CBR plot for sample TM 18 showing water content at compaction and observed CBR value for three compaction levels.

Appendix B. Data

B.1 Sieve Analysis

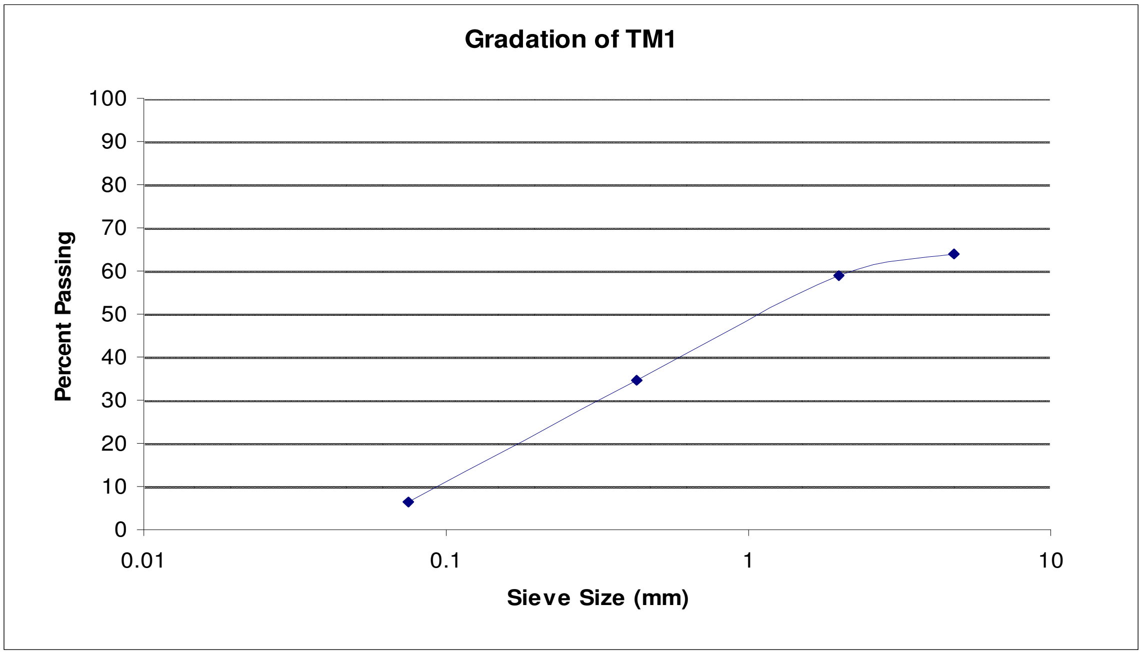

Figure B - 1. Gradation of soil sample TM 1.

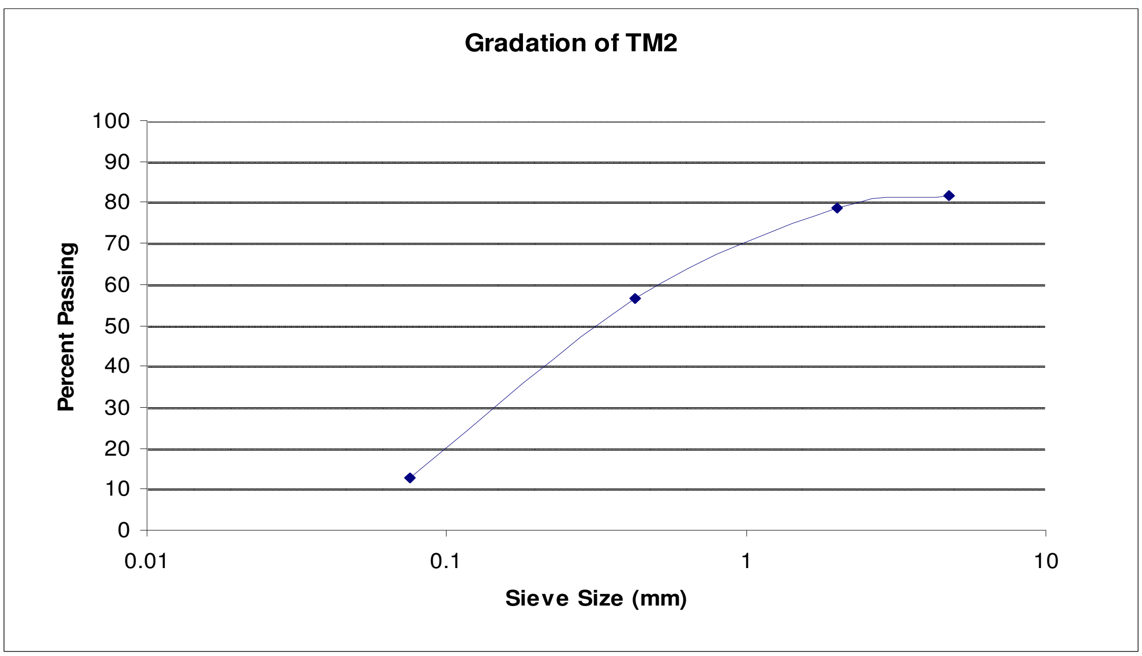

Figure B - 2. Gradation of soil sample TM 2.

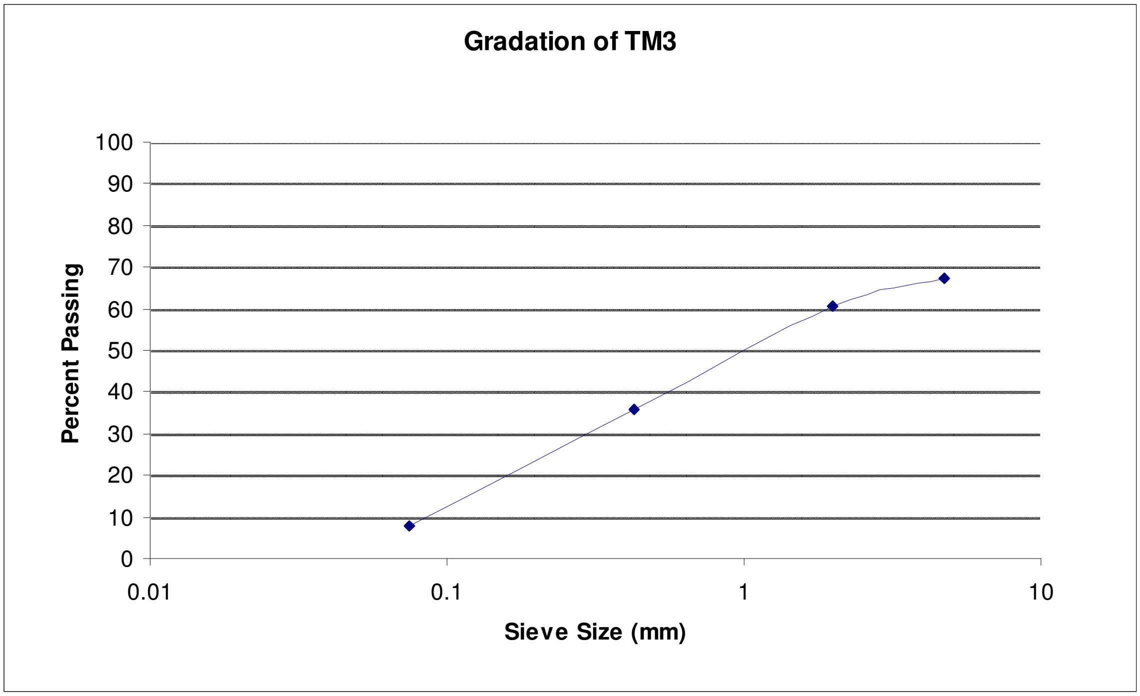

Figure B - 3. Gradation of soil sample TM 3.

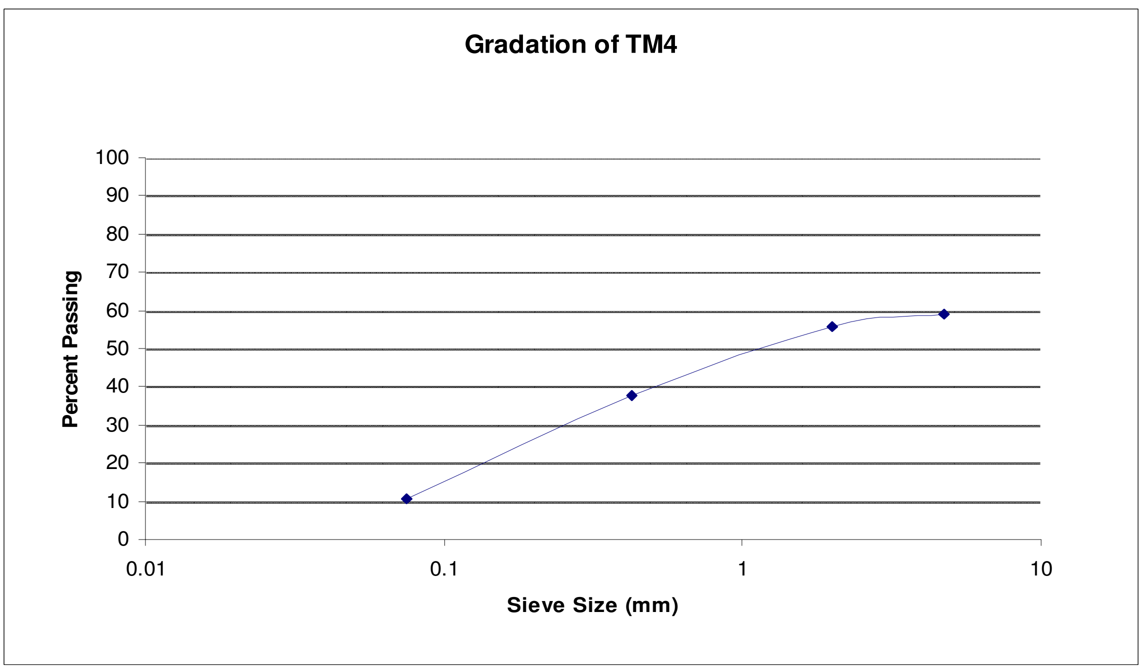

Figure B - 4. Gradation of soil sample TM 4.

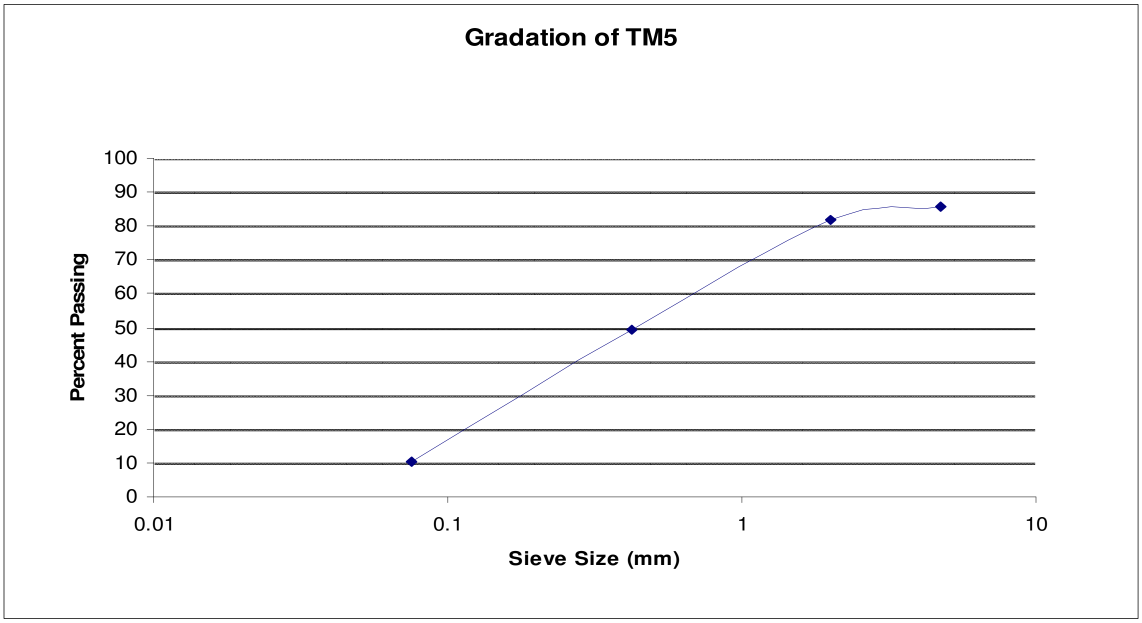

Figure B - 5. Gradation of soil sample TM 5.

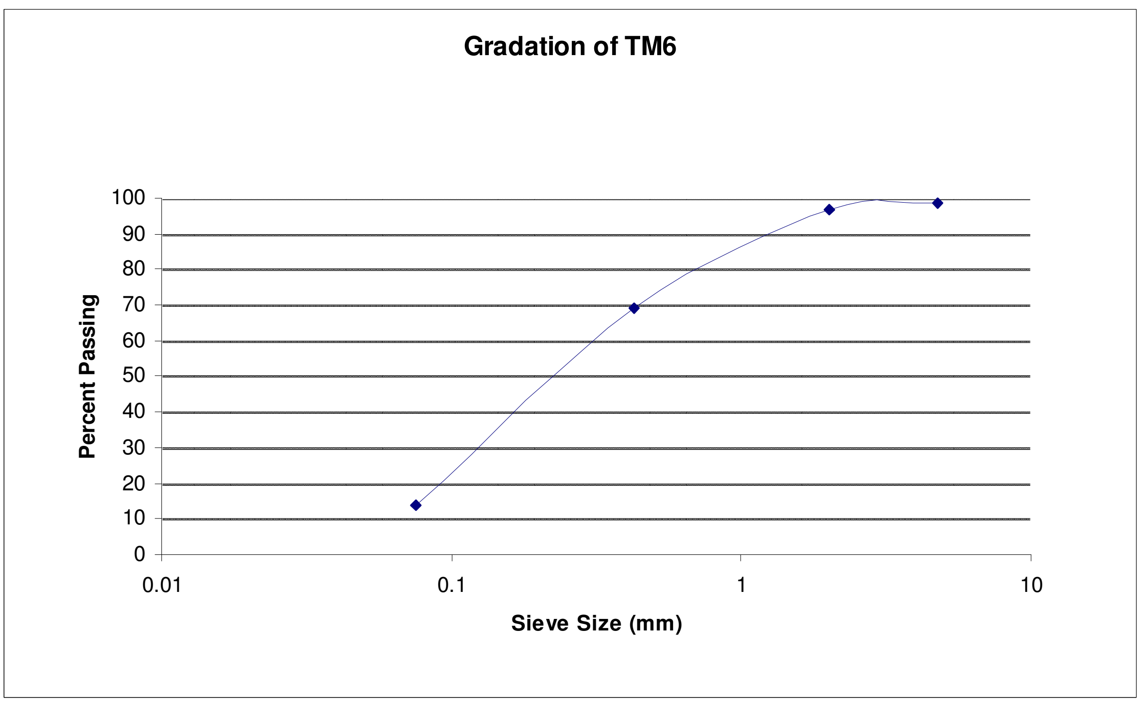

Figure B - 6. Gradation of soil sample TM 6.

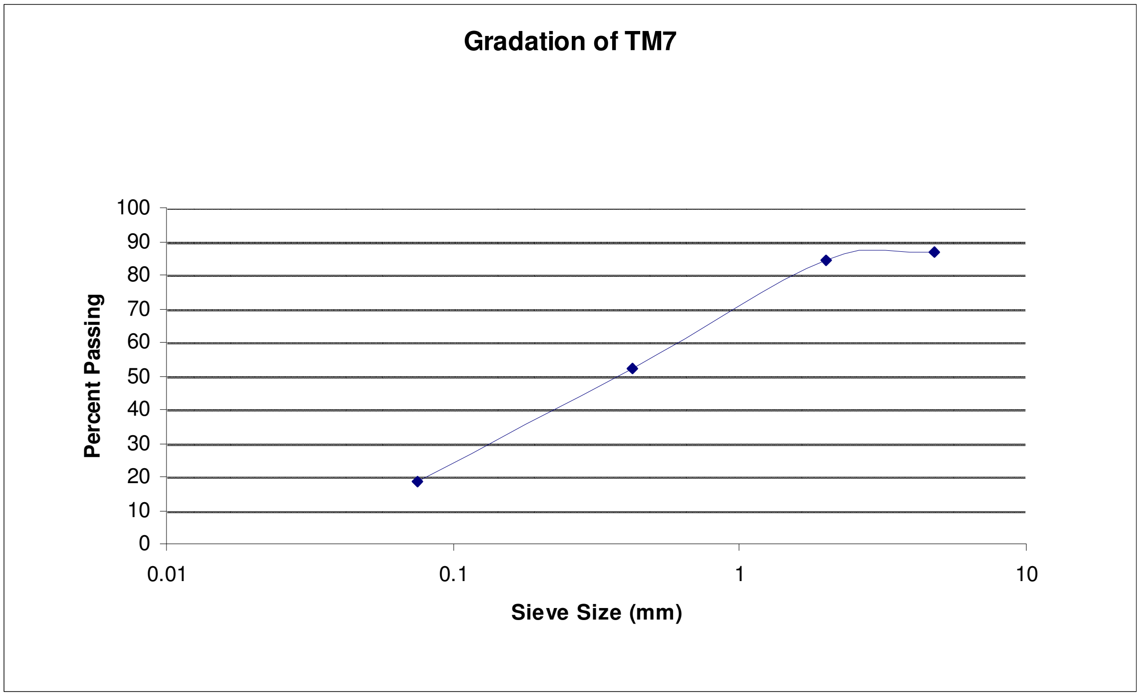

Figure B - 7. Gradation of soil sample TM 7.

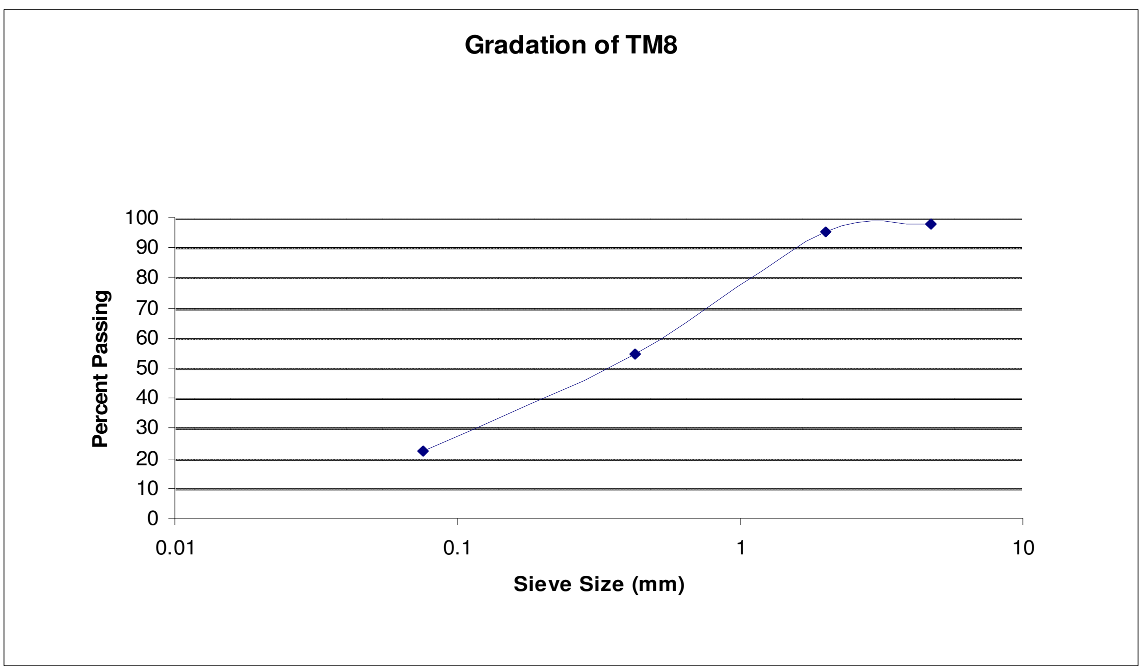

Figure B - 8. Gradation of soil sample TM 8.

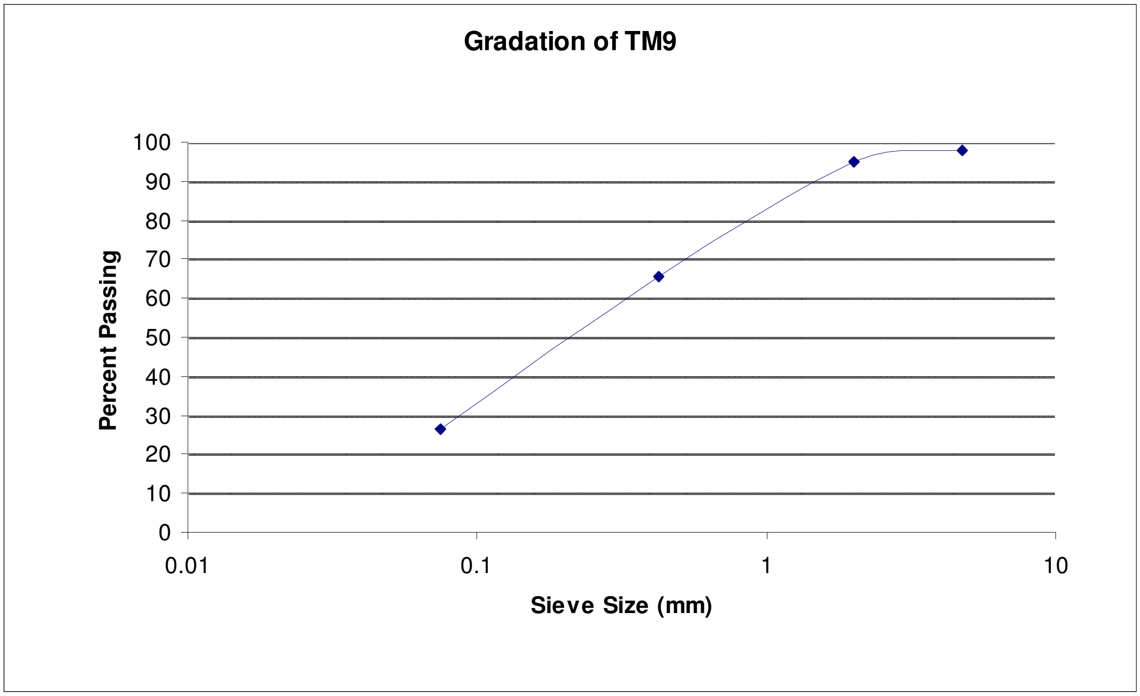

Figure B - 9. Gradation of soil sample TM 9.

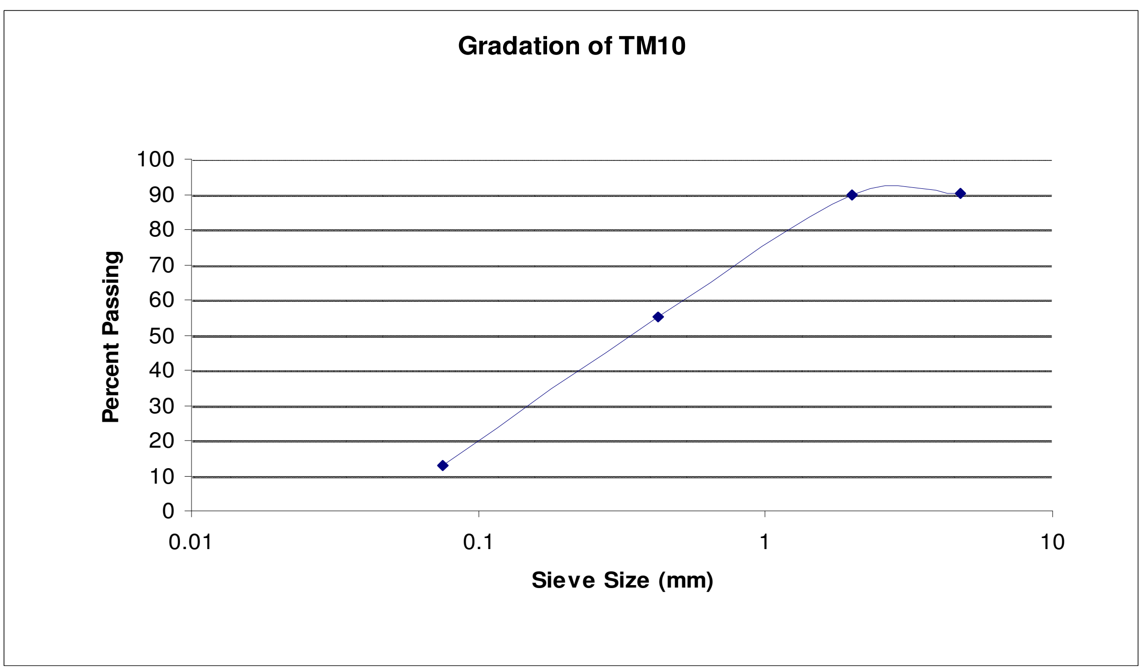

Figure B - 10. Gradation of soil sample TM 10.

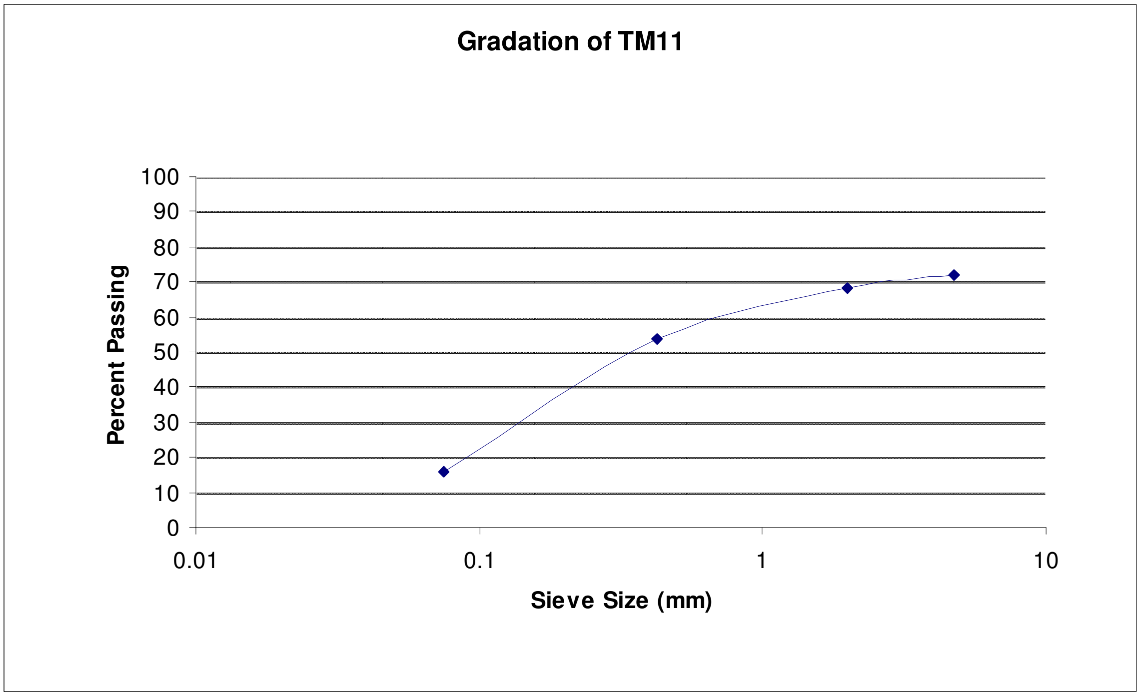

Figure B - 11. Gradation of soil sample TM 11.

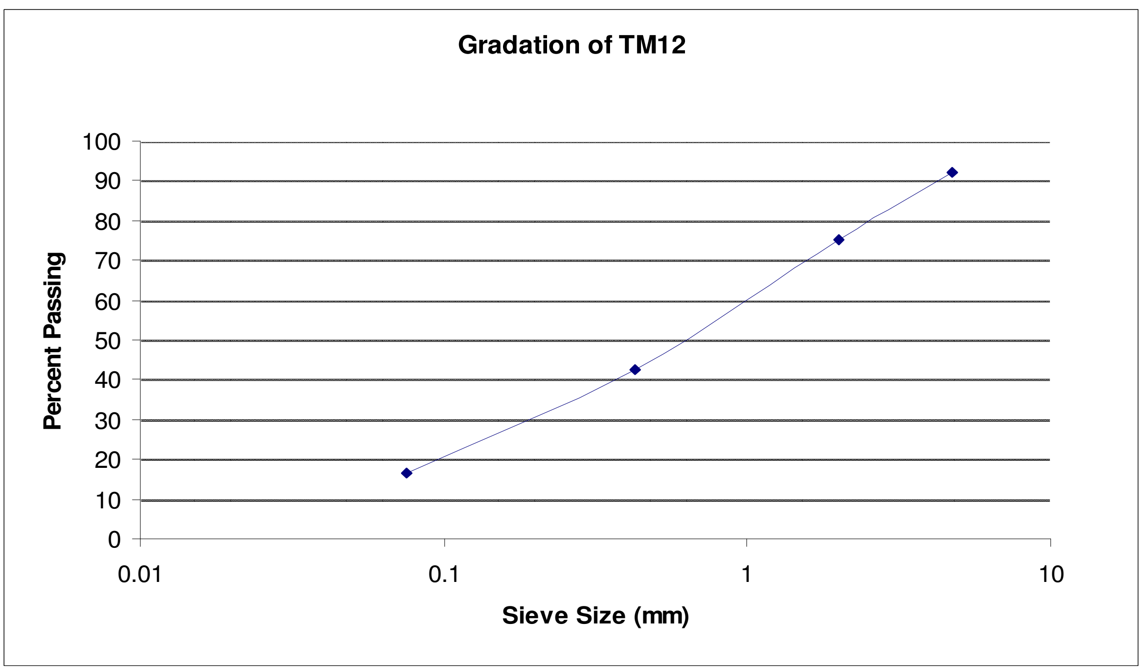

Figure B - 12. Gradation of soil sample TM 12.

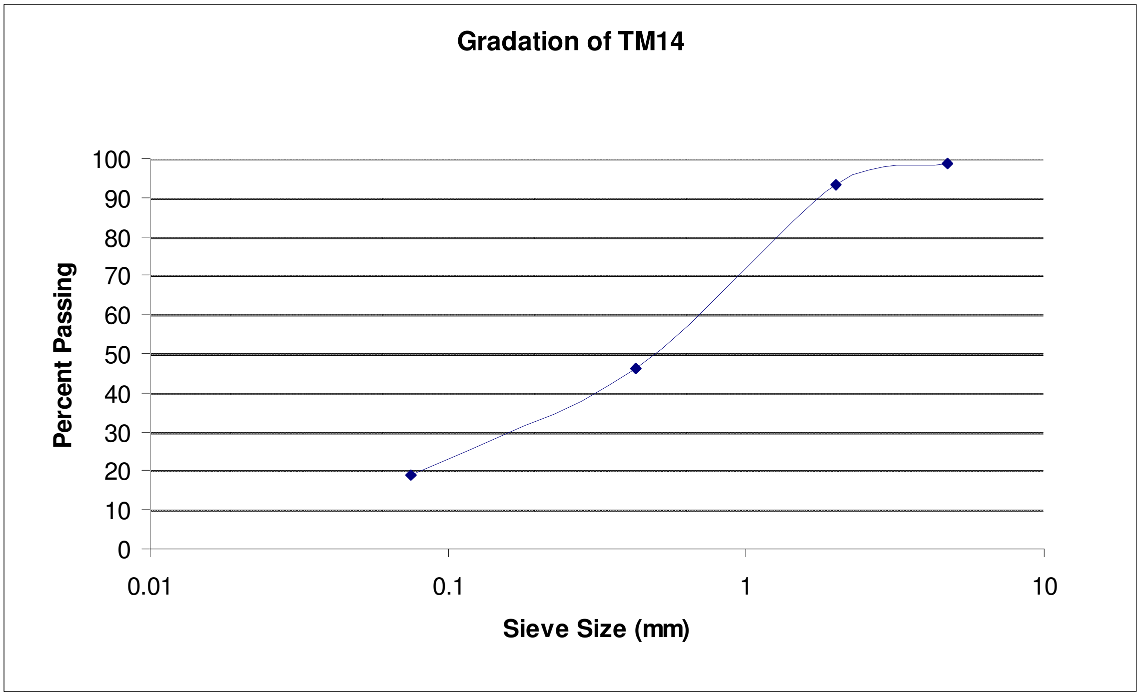

Figure B - 13. Gradation of soil sample TM 14.

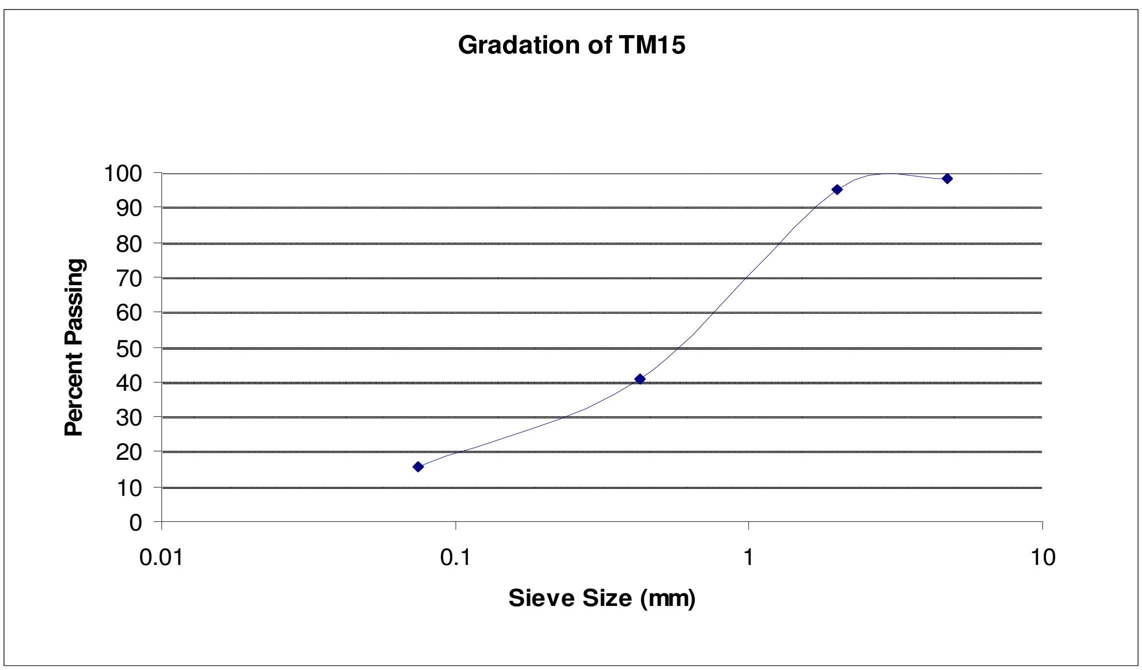

Figure B - 14. Gradation of soil sample TM 15.

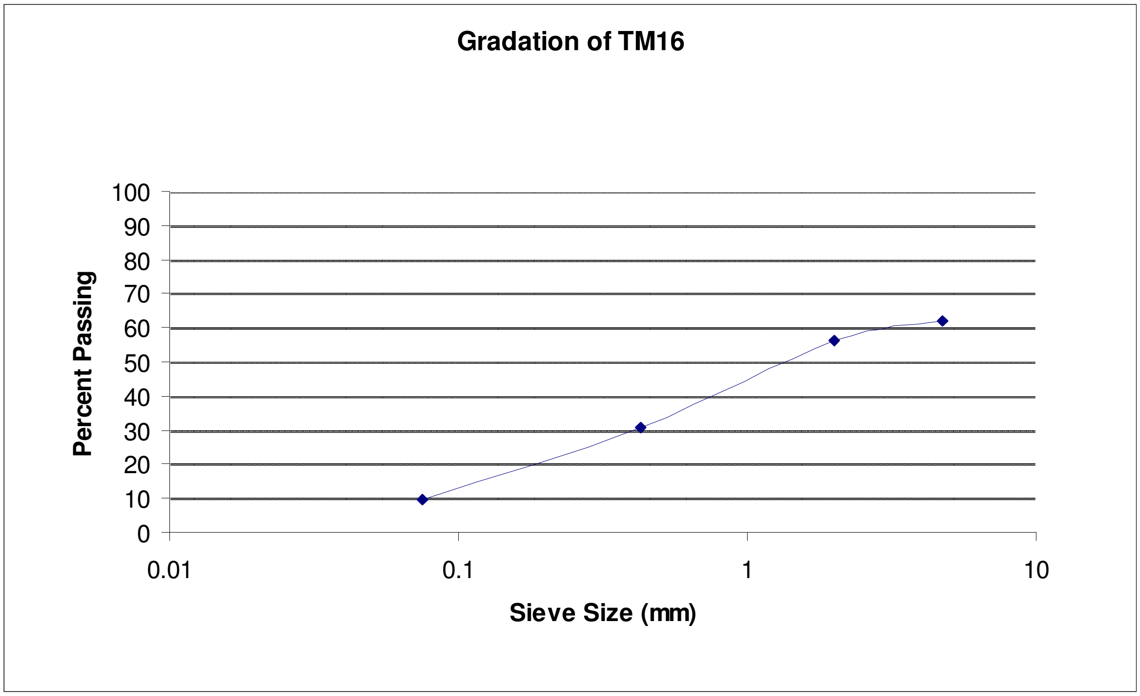

Figure B - 15. Gradation of soil sample TM 16.

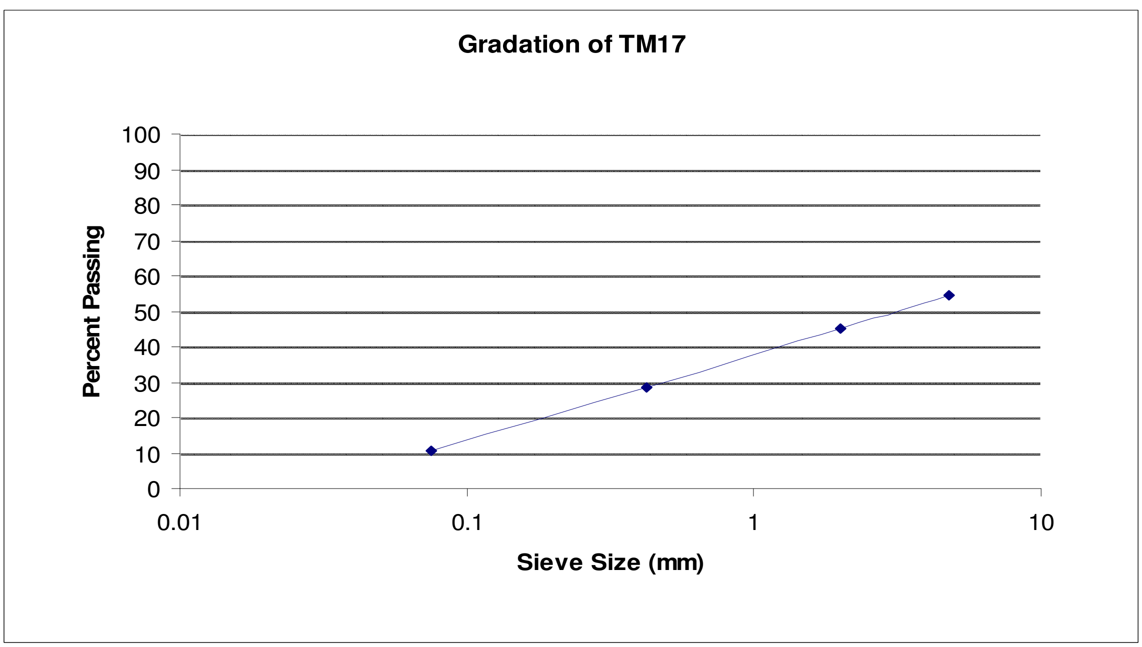

Figure B - 16. Gradation of soil sample TM 17.

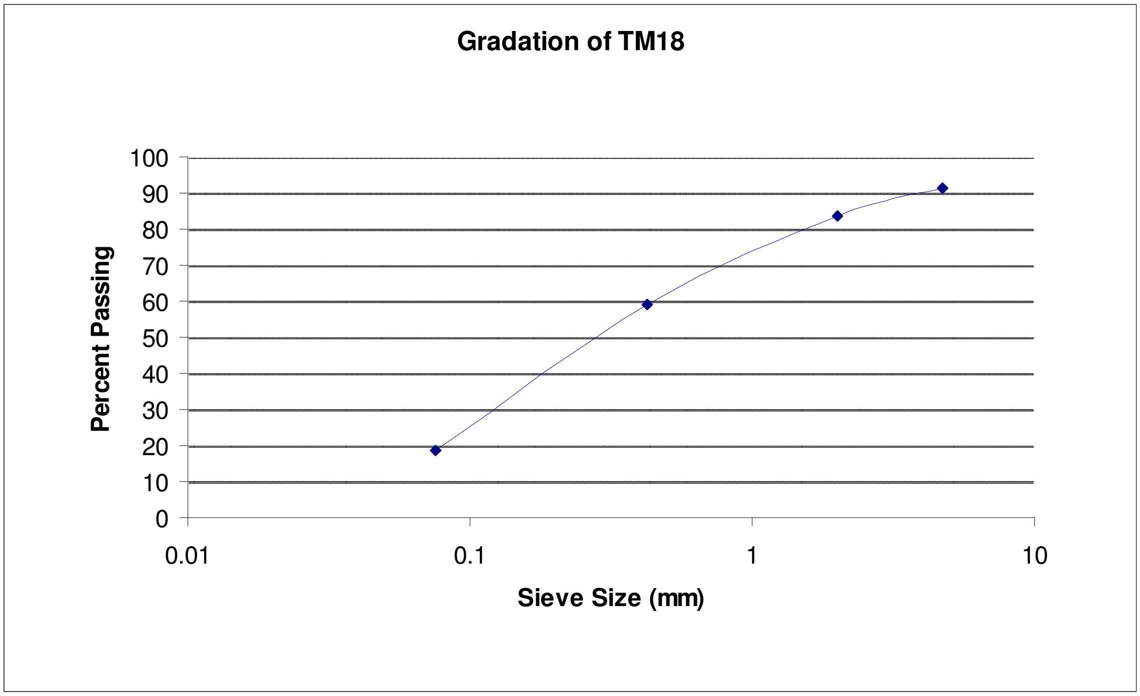

Figure B - 17. Gradation of soil sample TM 18.

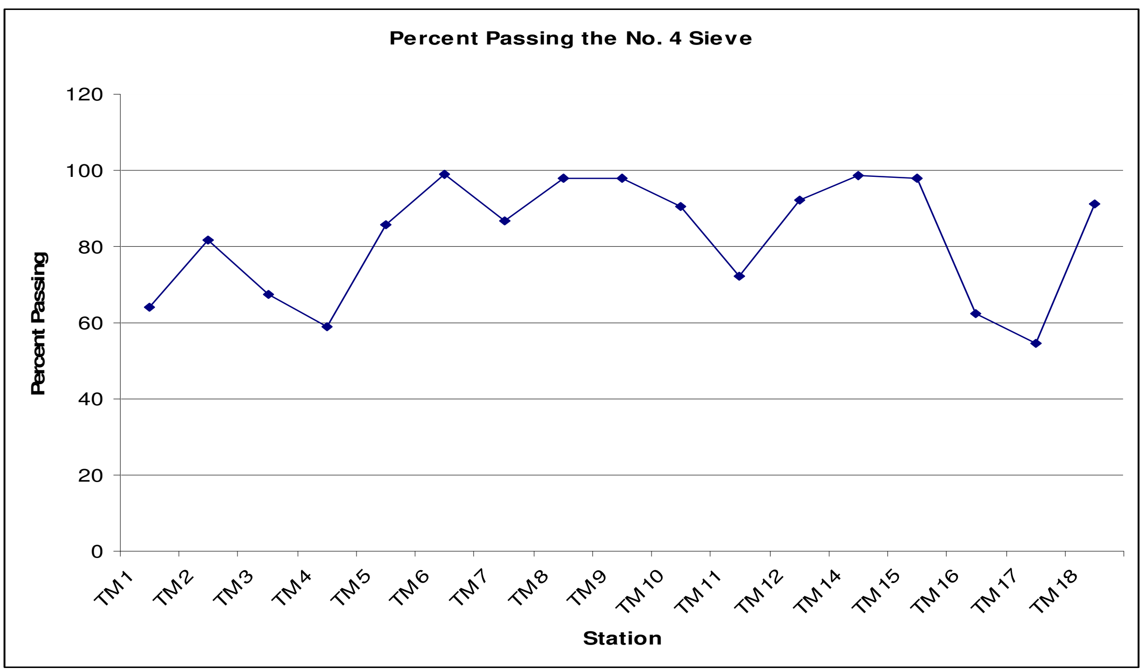

Figure B - 18. Percent passing the No. 4 sieve for each station, values ranging from 55% to 99%.

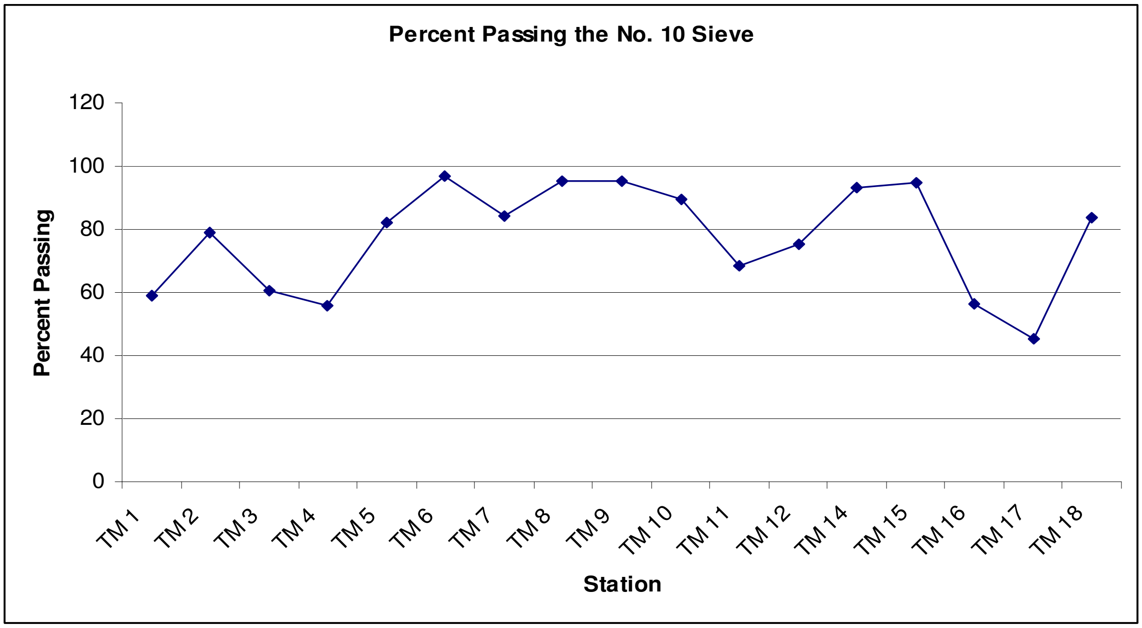

Figure B - 19. Percent passing the No. 10 sieve for each station, values ranging from 45% to 97%.

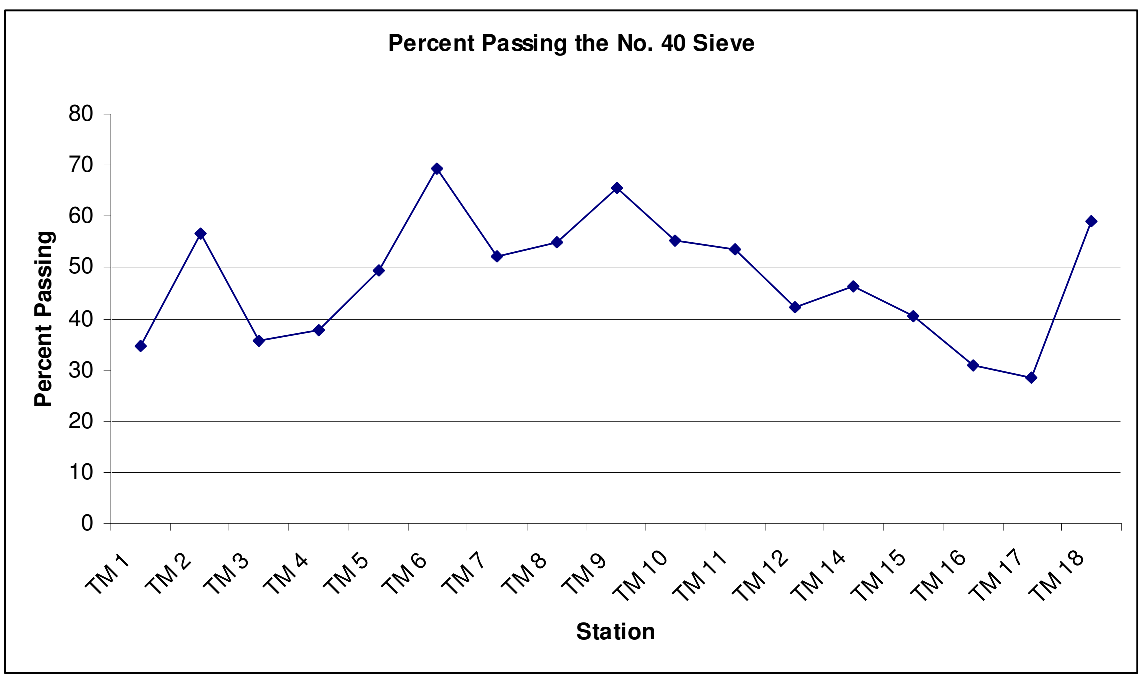

Figure B - 20. Percent passing the No. 40 sieve for each station, values ranging from 29% to 69%.

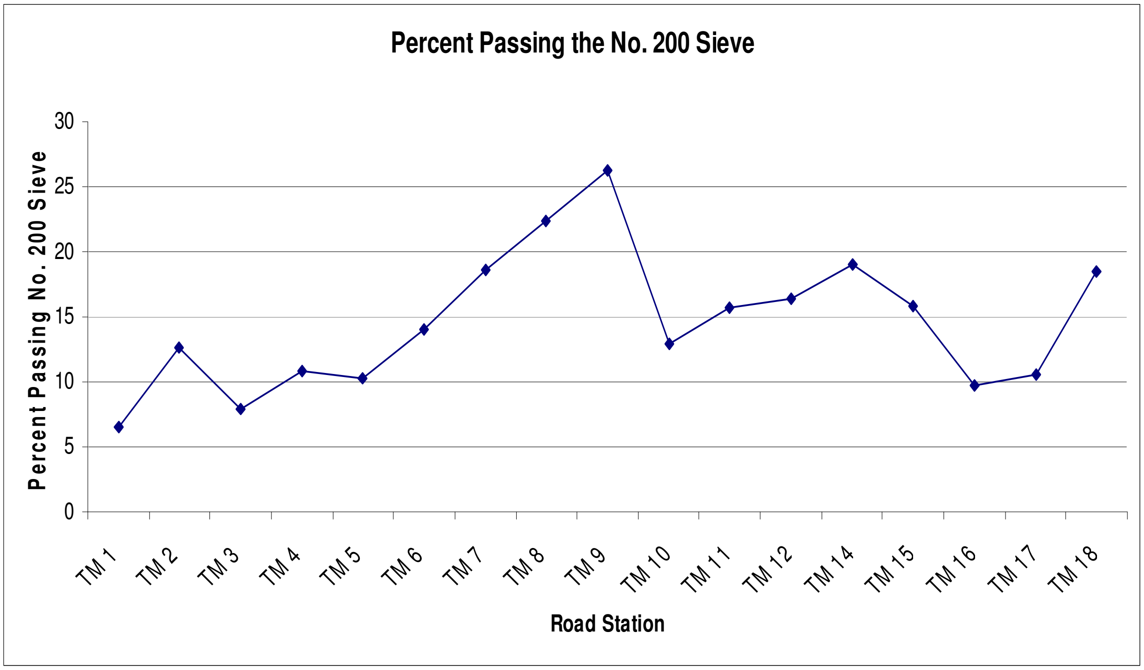

Figure B - 21. Percent passing the No. 200 sieve for each station, values ranging from 7% to 26%.

B.2 Atterberg Limits

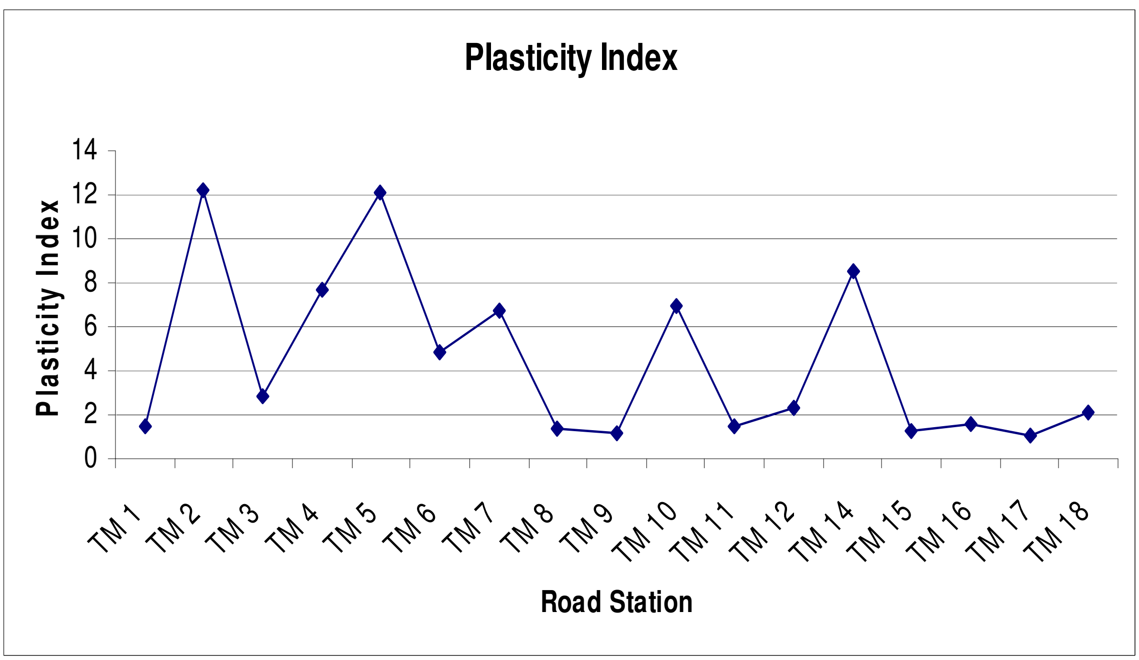

Figure B - 22. Plasticity index at each station, values range from 1 to 12.

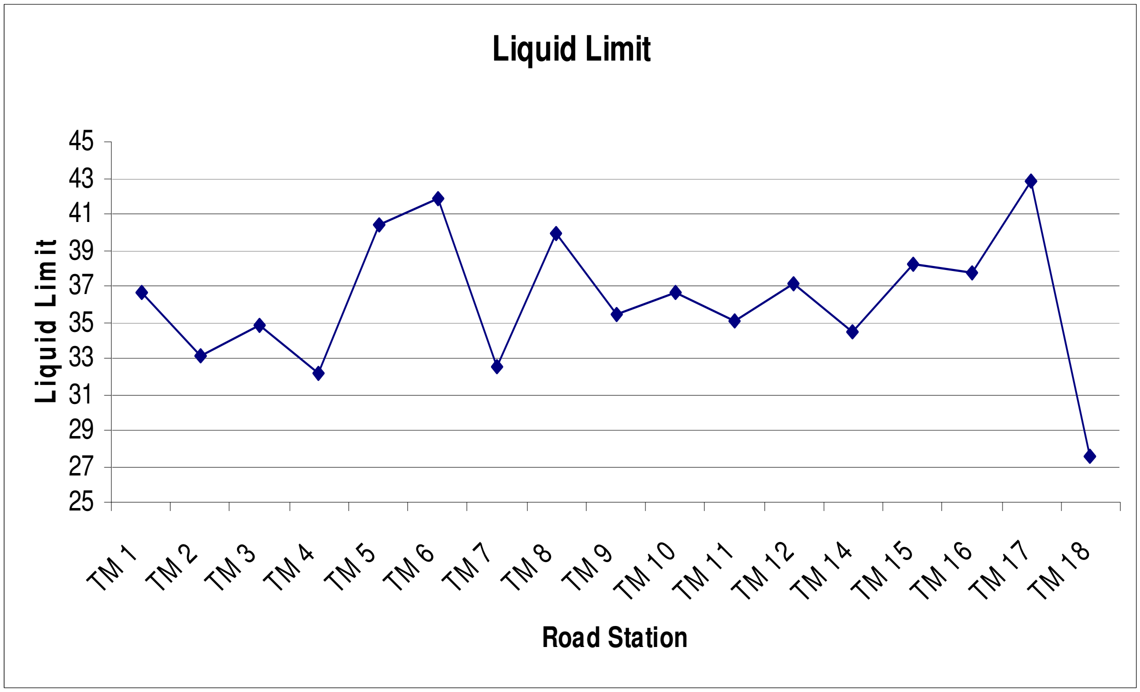

Figure B - 23. Liquid limit at each station, values range from 28 to 43.

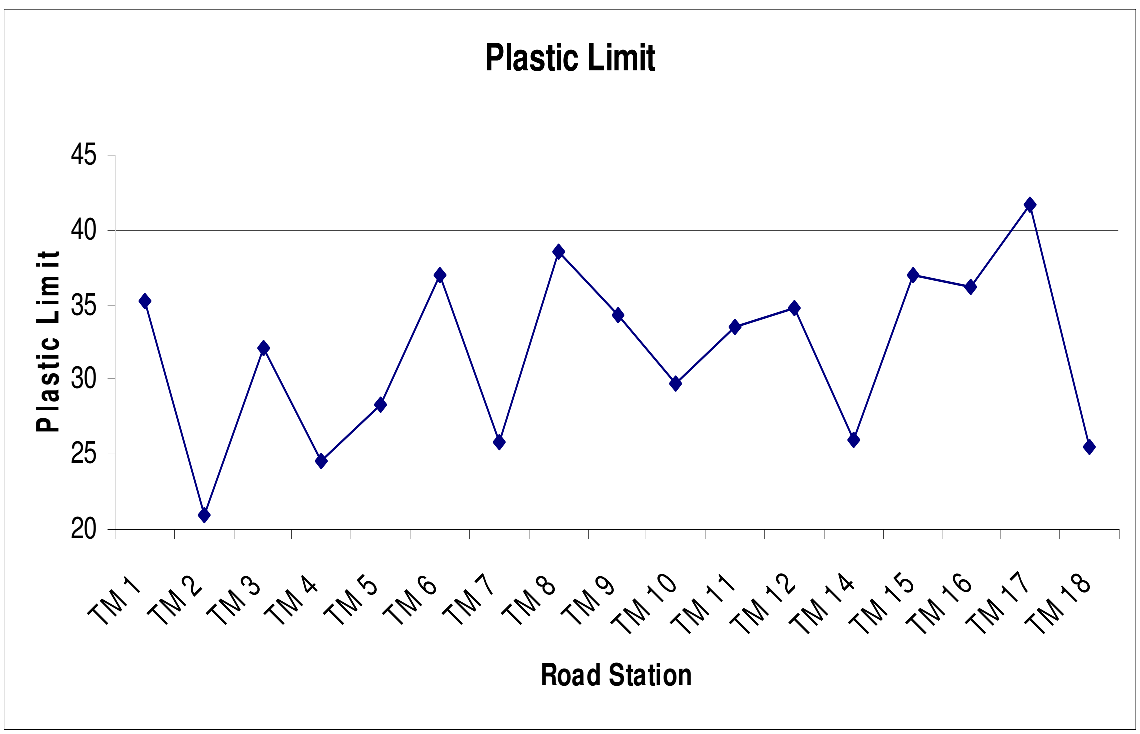

Figure B - 24. Plastic limit at each station, values range from 21 to 42.

B.3 Aggregate Testing

Figure B - 25. Gradation of both base coarse and surface aggregate.

B.4 Data Snooping

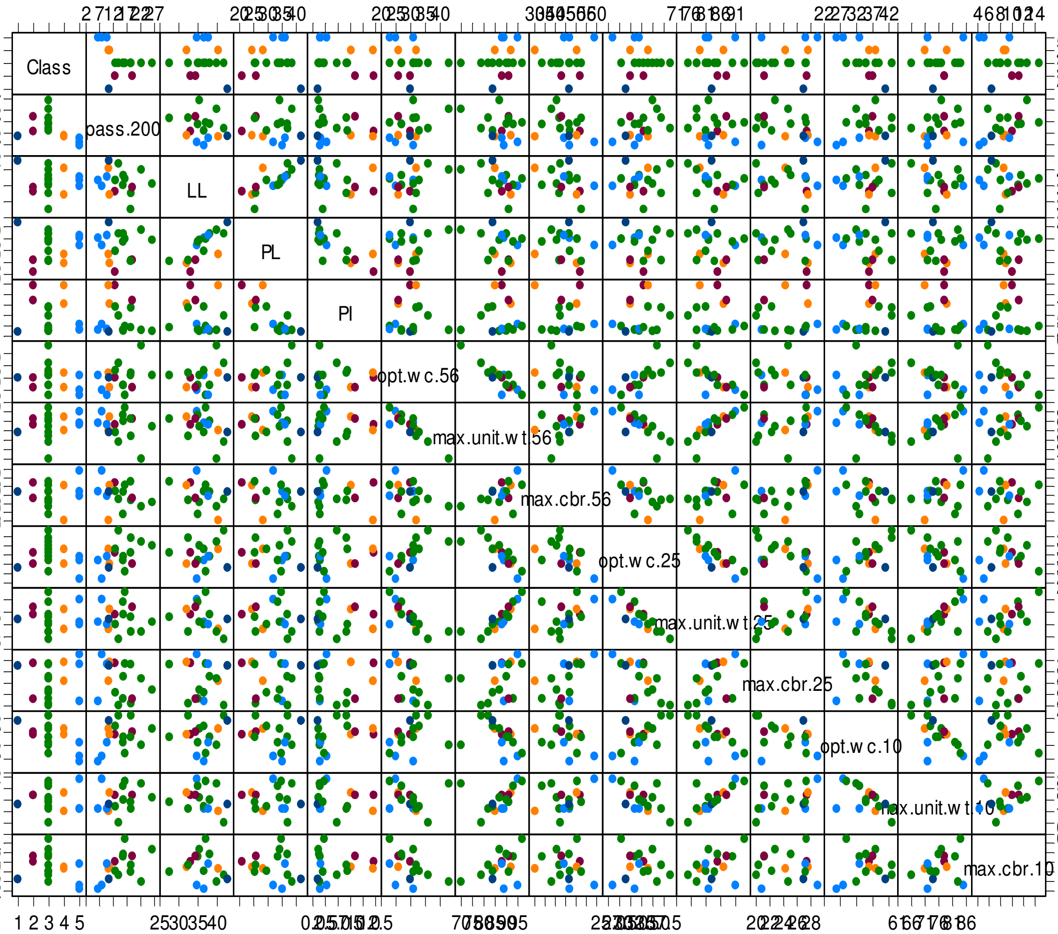

Figure B - 26. Matrix plot of data snooping variables.

Table B - 1. Correlation plot of data snooping variables.

	pass 200	LL	PL	PI	W% 56	Unit wt 56	CBR 56	W% 25	Unit wt 25	CBR 25	W% 10	Unit wt 10
pass 200	1	-0.19	-0.01	-0.18	0.34	-0.28	-0.30	0.44	-0.10	-0.28	0.28	0.21
LL	-0.19	1	0.76	-0.15	0.28	-0.47	-0.41	0.14	-0.36	-0.15	0.15	-0.27
PL	-0.01	0.76	1	-0.76	0.16	-0.28	-0.19	-0.03	-0.15	-0.06	-0.15	-0.04
PI	-0.18	-0.15	-0.76	1	0.05	-0.04	-0.12	0.18	-0.13	-0.06	0.38	-0.21
W% 56	0.34	0.28	0.16	0.05	1	-0.90	-0.38	0.74	-0.74	-0.39	0.32	-0.26
Unit wt 56	-0.28	-0.47	-0.28	-0.04	-0.90	1	0.45	-0.76	0.85	0.35	-0.44	0.37
CBR 56	-0.30	-0.41	-0.19	-0.12	-0.38	0.45	1	-0.51	0.45	0.59	-0.32	0.28
W% 25	0.44	0.14	-0.03	0.18	0.74	-0.76	-0.51	1	-0.86	-0.57	0.61	-0.60
Unit wt 25	-0.10	-0.36	-0.15	-0.13	-0.74	0.85	0.45	-0.86	1	0.45	-0.56	0.77
CBR 25	-0.28	-0.15	-0.06	-0.06	-0.39	0.35	0.59	-0.57	0.45	1	-0.35	0.46
w% 10	0.28	0.15	-0.15	0.38	0.32	-0.44	-0.32	0.61	-0.56	-0.35	1	-0.59
Unit wt 10	0.21	-0.27	-0.04	-0.21	-0.26	0.37	0.28	-0.60	0.77	0.46	-0.59	1
CBR 10	0.49	-0.18	-0.16	0.07	-0.48	0.42	-0.15	-0.06	0.43	0.00	0.10	0.24

B.4.1 Insignificant Figures

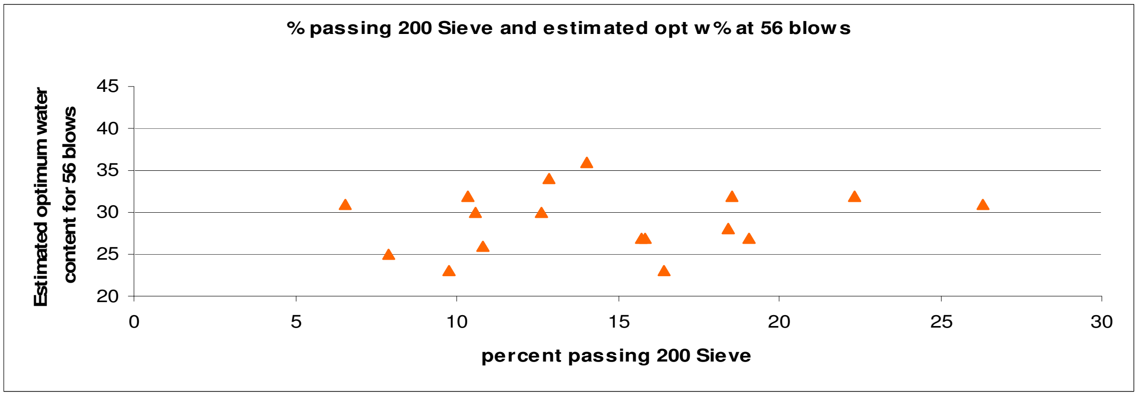

Figure B - 27. Percent passing No. 200 sieve compared to optimum water content for highest compaction level.

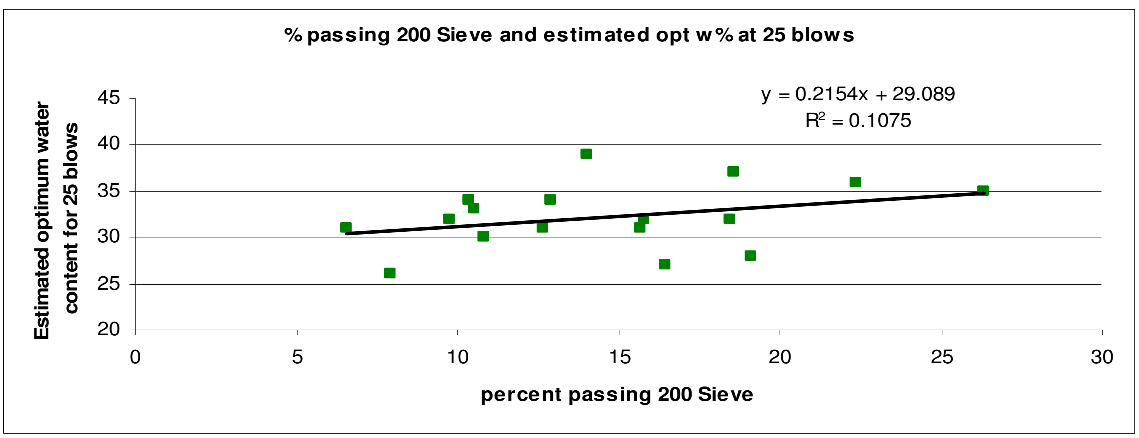

Figure B - 28. Percent passing No. 200 sieve compared to optimum water content for middle compaction level.

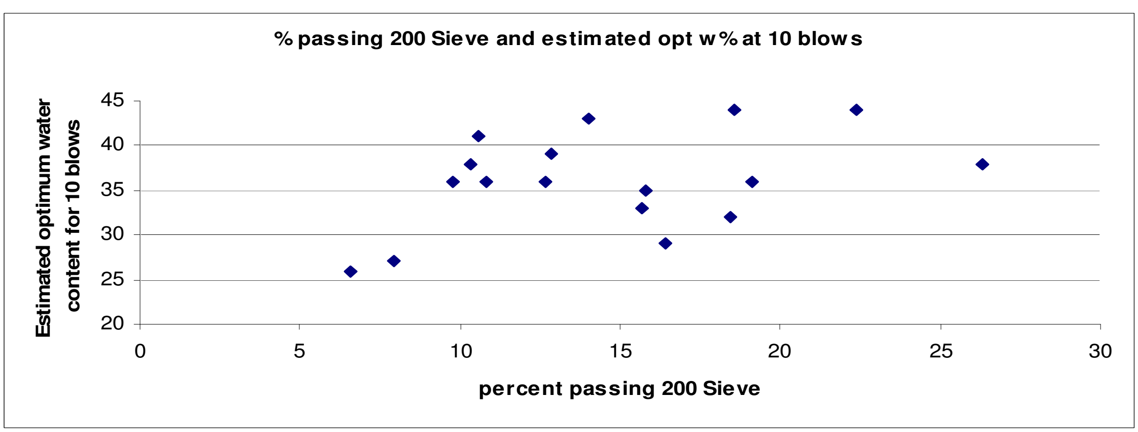

Figure B - 29. Percent passing No. 200 sieve compared to optimum water content for lowest compaction level.

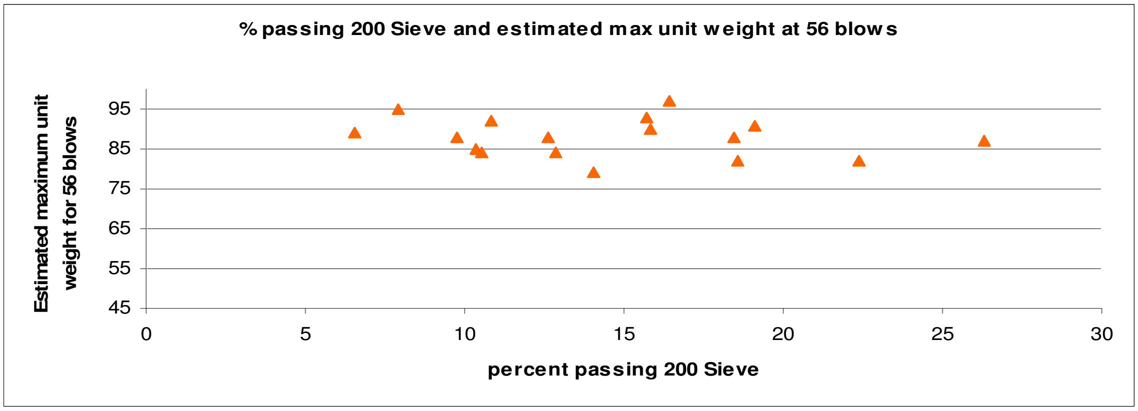

Figure B - 30. Percent passing the No. 200 sieve compared to maximum unit weight for the highest compaction level.

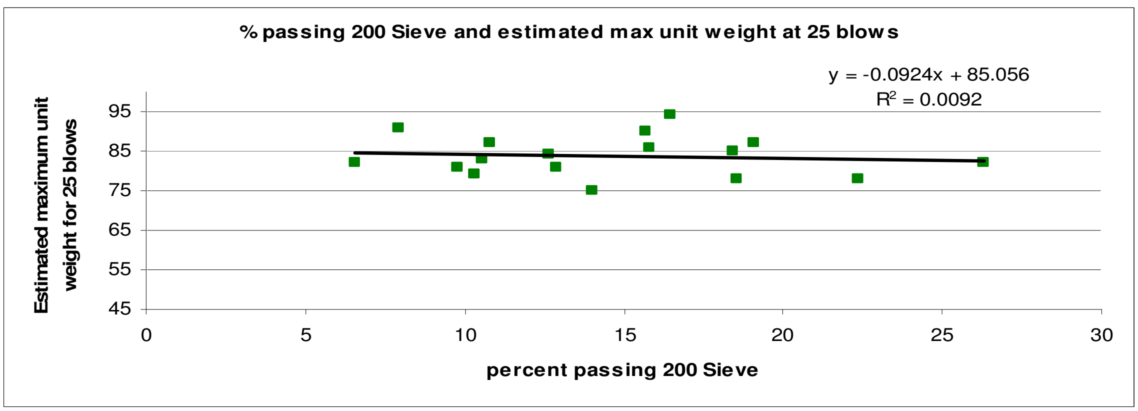

Figure B - 31. Percent passing No. 200 sieve compared to maximum unit weight for middle compaction level.

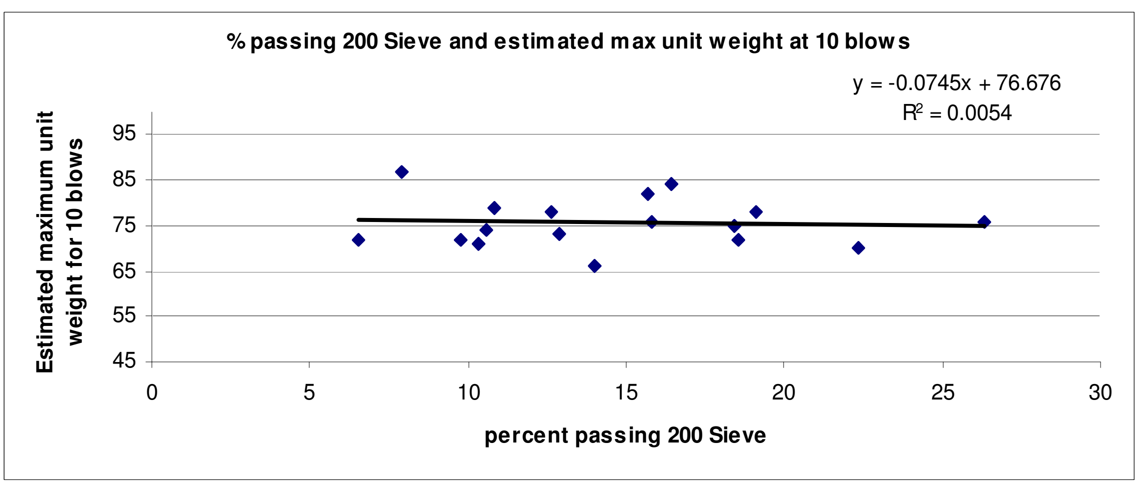

Figure B - 32. Percent passing No. 200 sieve compared to maximum unit weight for lowest compaction level.

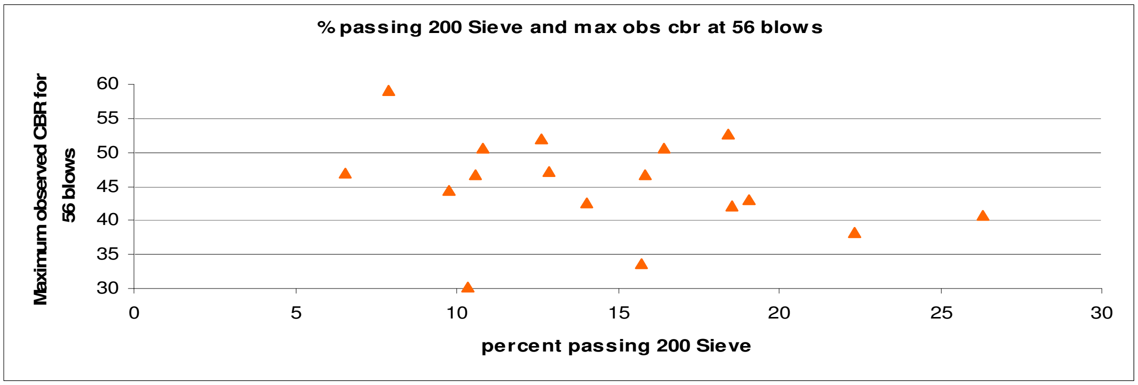

Figure B - 33. Percent passing No. 200 sieve compared to maximum observed CBR for highest compaction level.

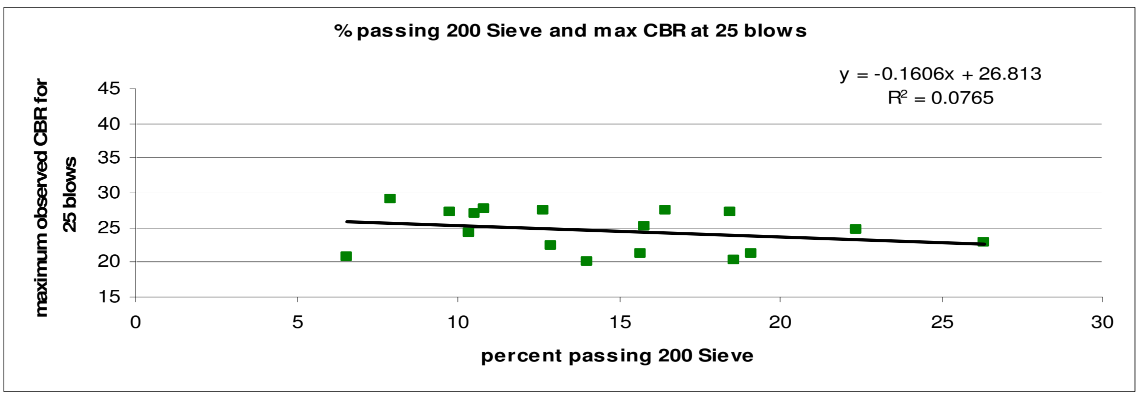

Figure B - 34. Percent passing No. 200 sieve compared to maximum observed CBR for middle compaction level.

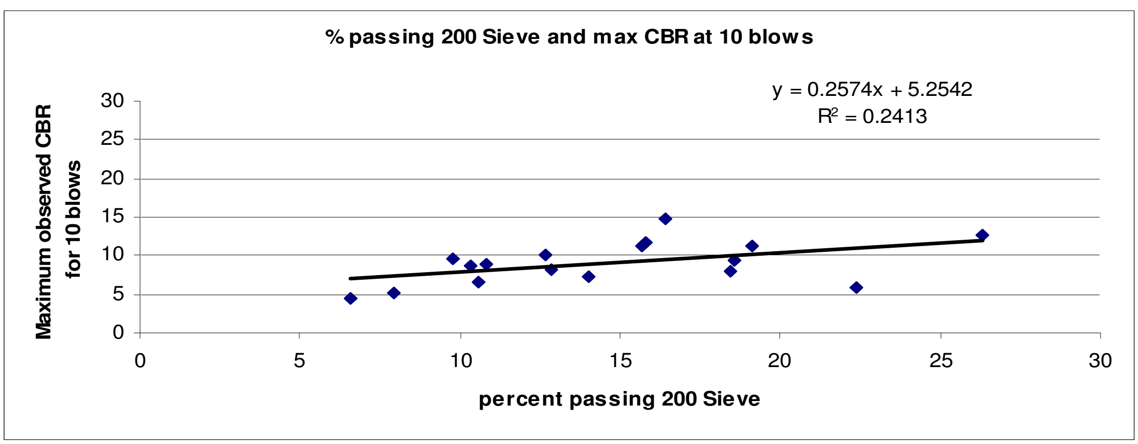

Figure B - 35. Percent passing No. 200 sieve compared to maximum observed CBR for lowest compaction level.

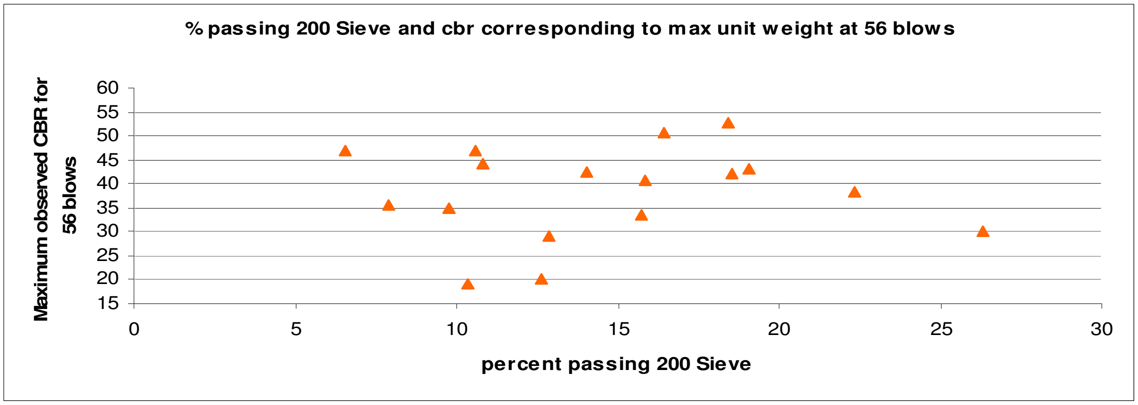

Figure B - 36. Percent passing No. 200 sieve compared to CBR corresponding to maximum unit weight for highest compaction level.

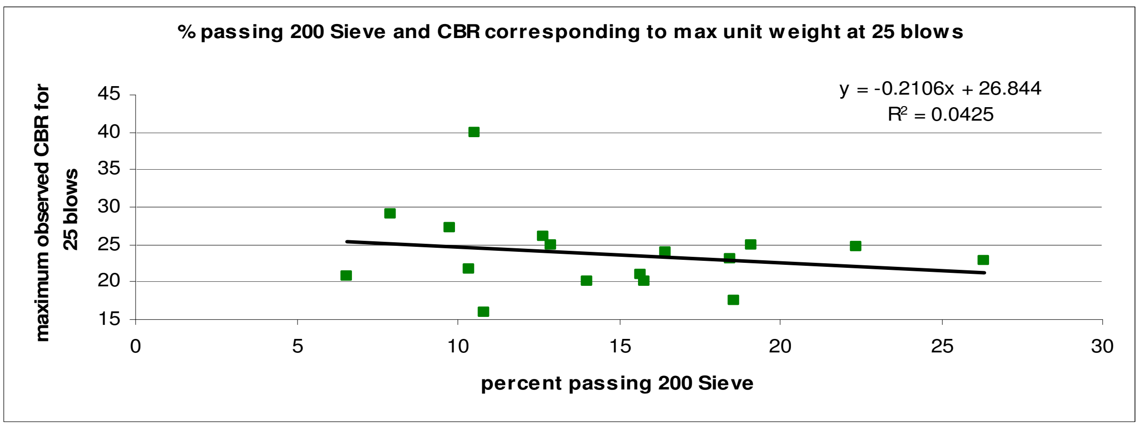

Figure B - 37. Percent passing No. 200 sieve compared to CBR corresponding to maximum unit weight for middle compaction level.

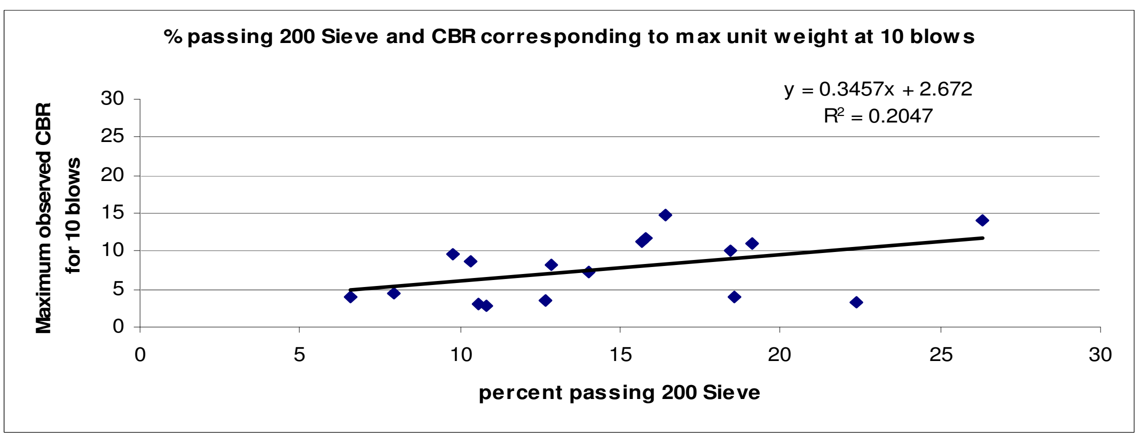

Figure B - 38. Percent passing No. 200 sieve compared to CBR corresponding to maximum unit weight for lowest compaction level.

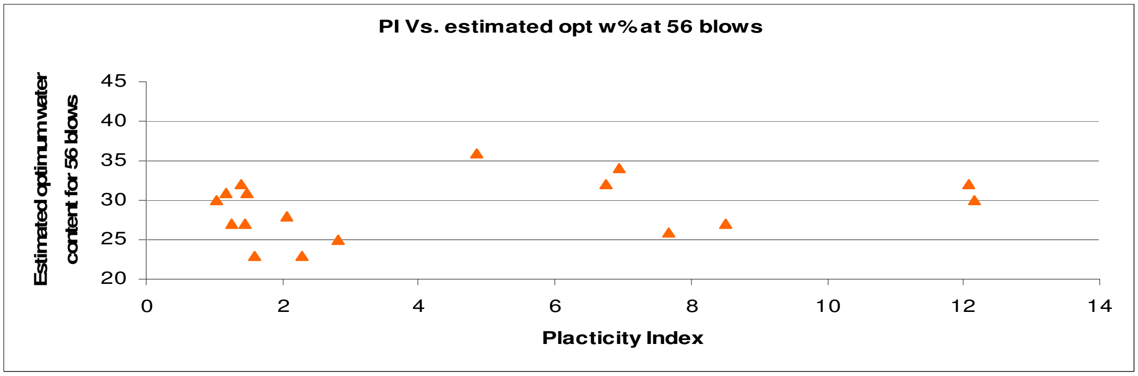

Figure B - 39. Plasticity Index compared to optimum water content for highest compaction level.

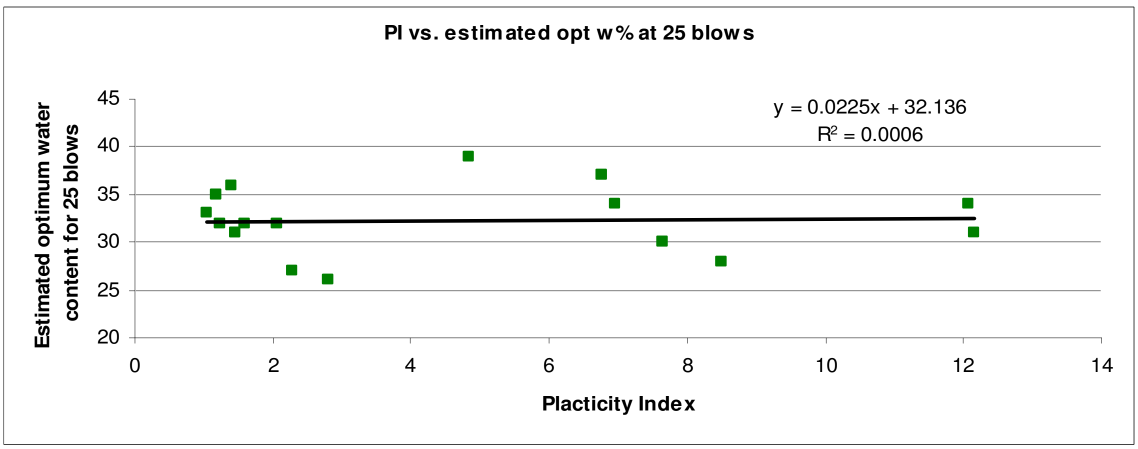

Figure B - 40. Plasticity Index compared to optimum water content for middle compaction level.

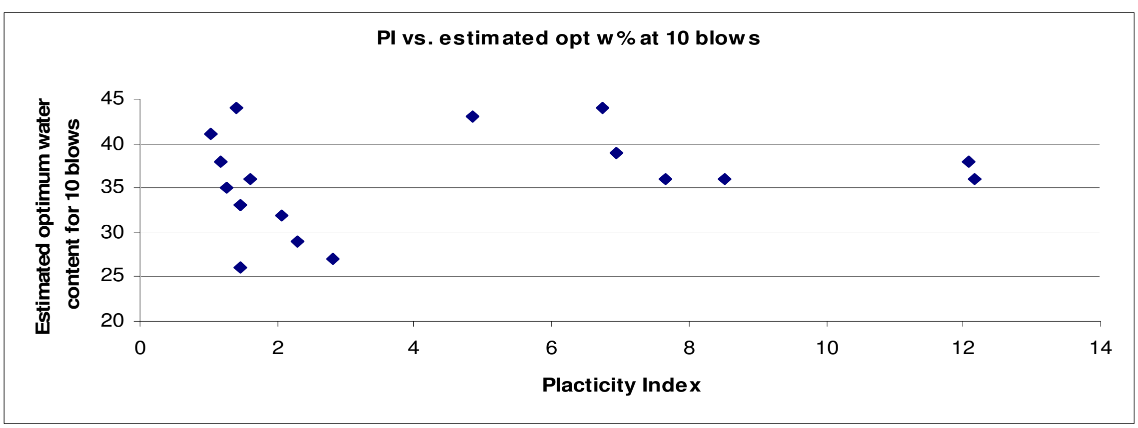

Figure B - 41. Plasticity Index compared to optimum water content for lowest compaction level.

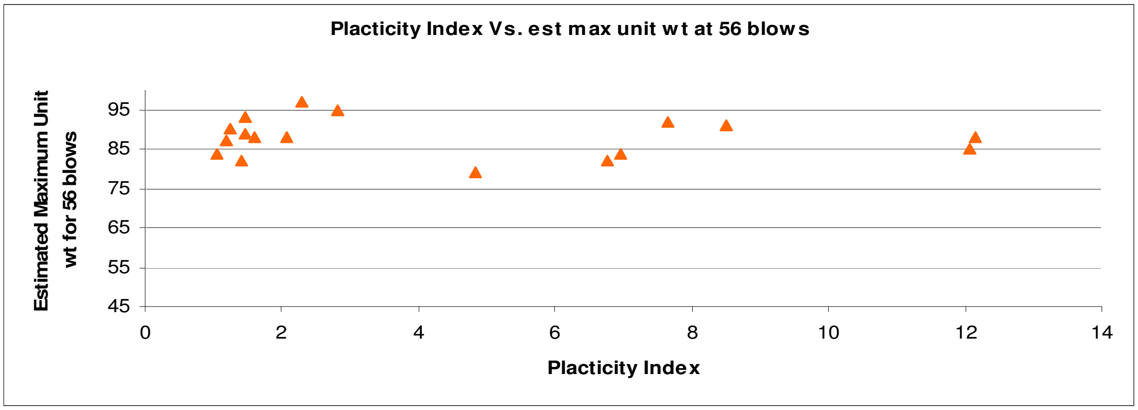

Figure B - 42. Plasticity Index compared to maximum unit weight for highest compaction level.

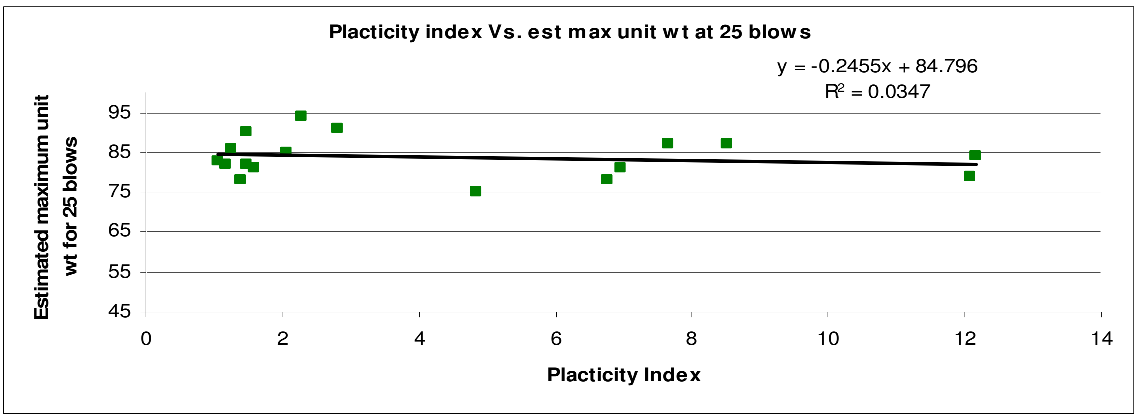

Figure B - 43. Plasticity Index compared to maximum unit weight for middle compaction level.

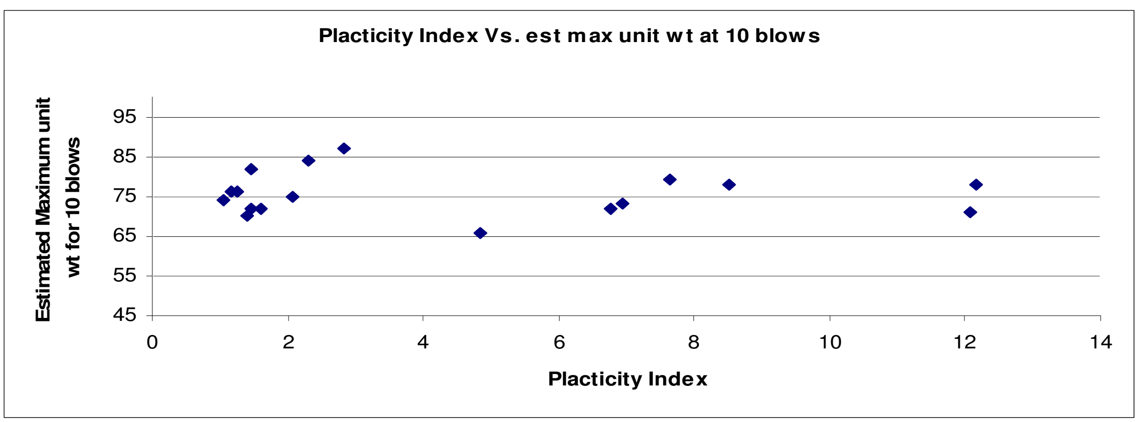

Figure B - 44. Plasticity Index compared to maximum unit weight for lowest compaction level.

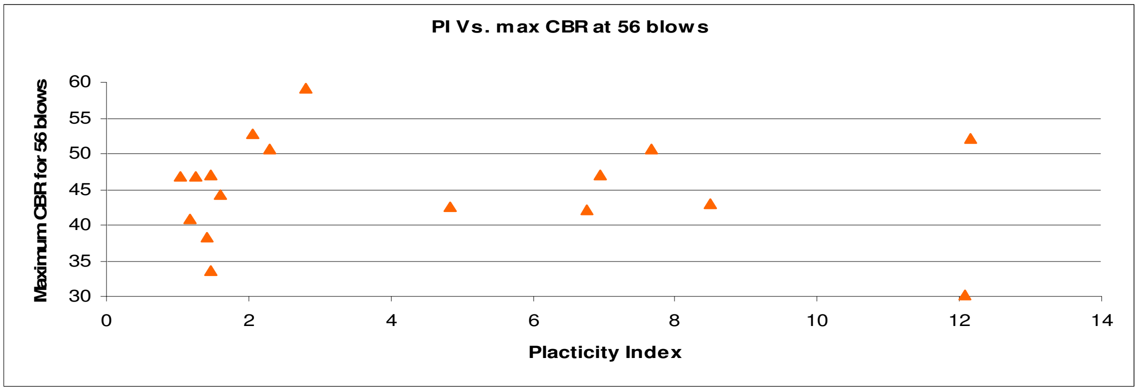

Figure B - 45. Plasticity Index compared to maximum CBR for highest compaction level.

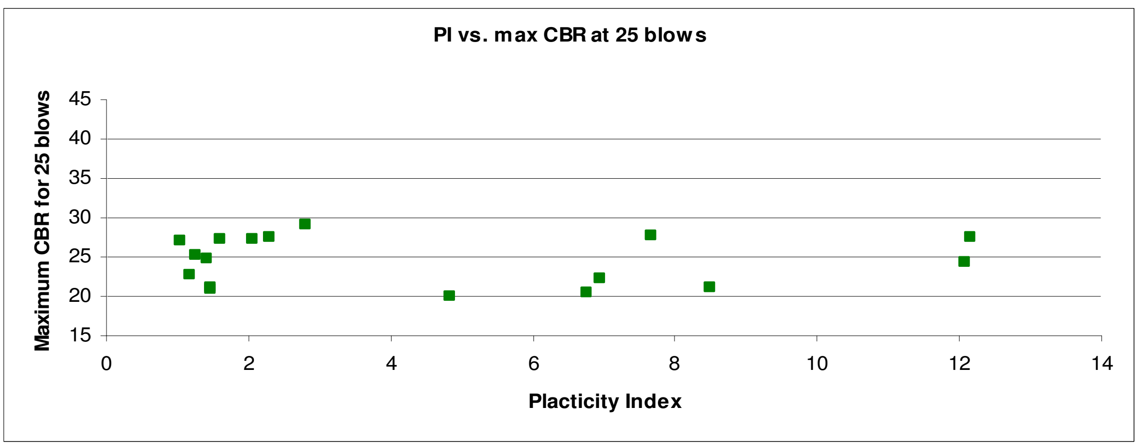

Figure B - 46. Plasticity Index compared to maximum CBR for middle compaction level.

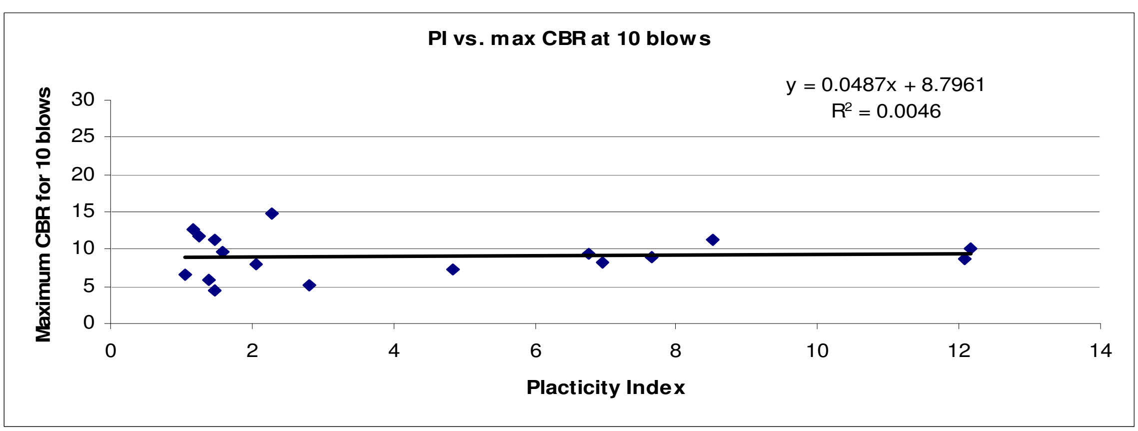

Figure B - 47. Plasticity Index compared to maximum CBR for lowest compaction level.

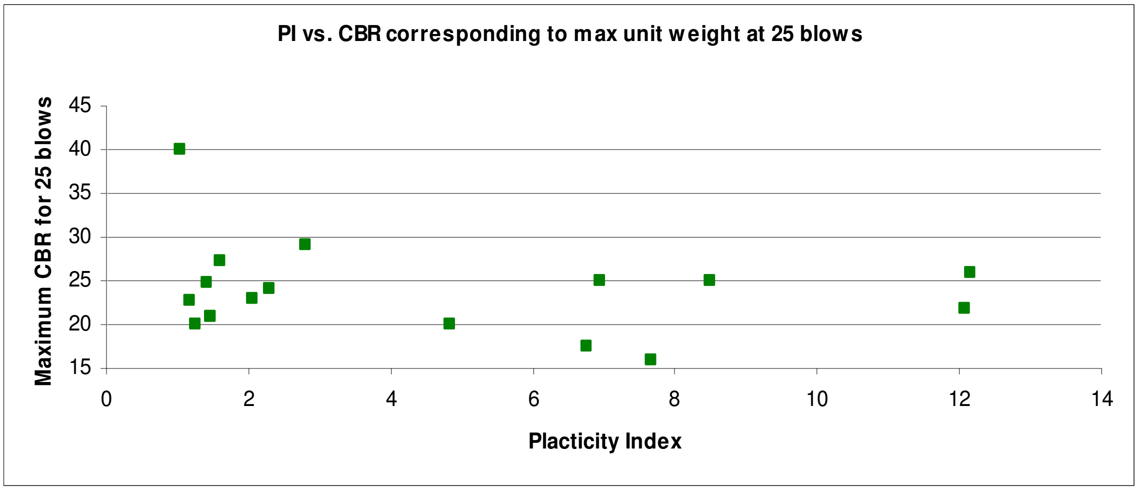

Figure B - 48. Plasticity Index compared to CBR corresponding to maximum unit weight for middle compaction level.

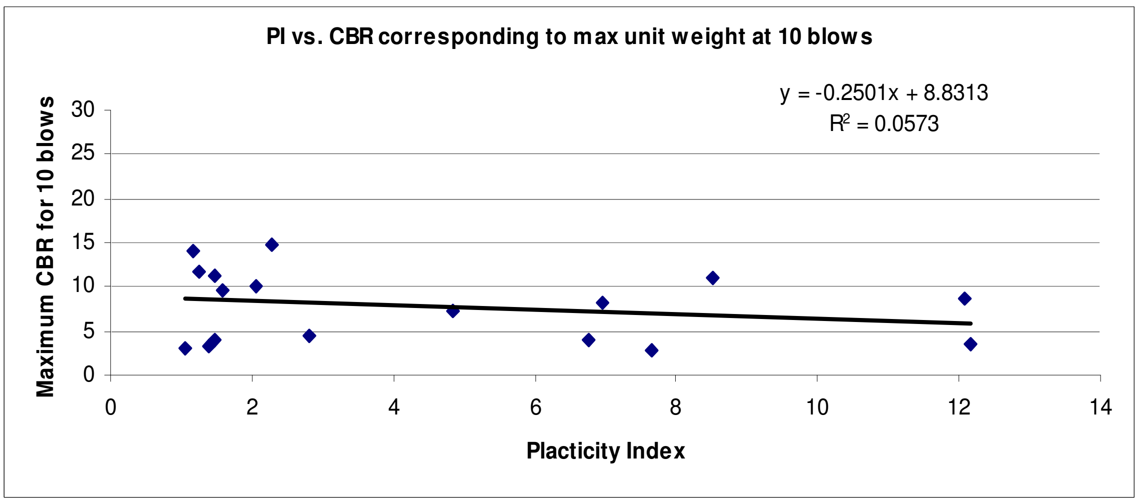

Figure B - 49. Plasticity Index compared to CBR corresponding to maximum unit weight for lowest compaction level.

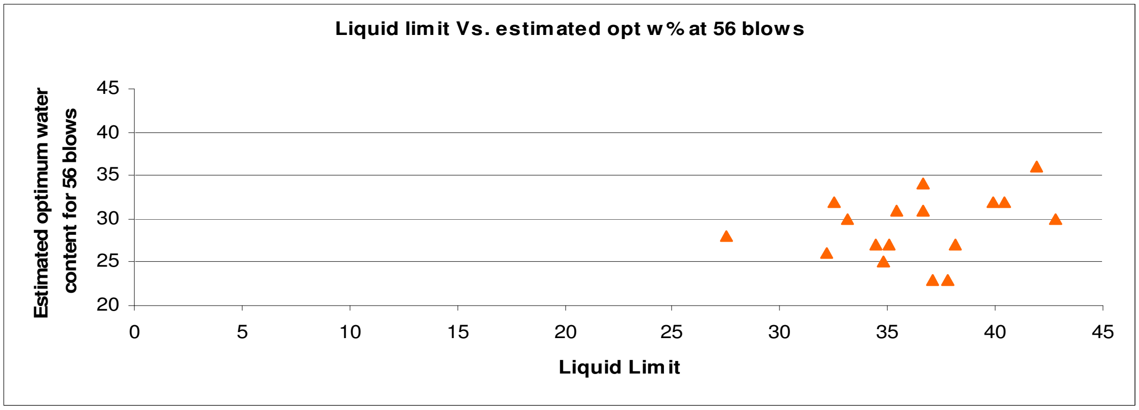

Figure B - 50. Liquid limit compared to optimum water content for highest compaction level.

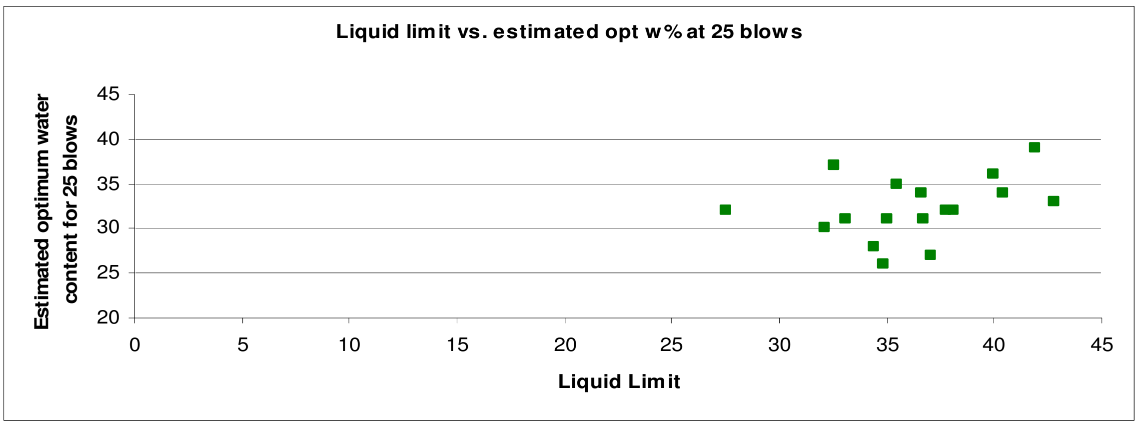

Figure B - 51. Liquid limit compared to optimum water content for middle compaction level.

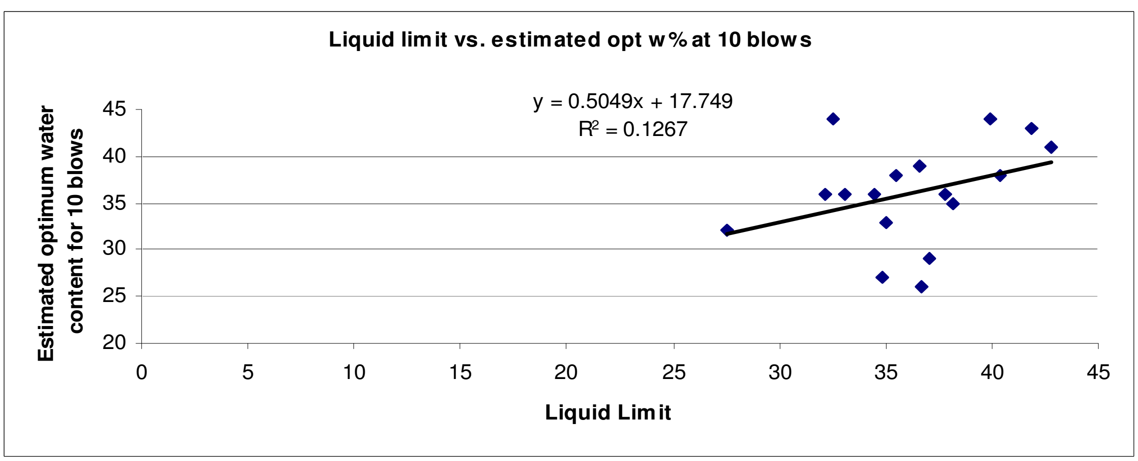

Figure B - 52. Liquid limit compared to optimum water content for lowest compaction level.

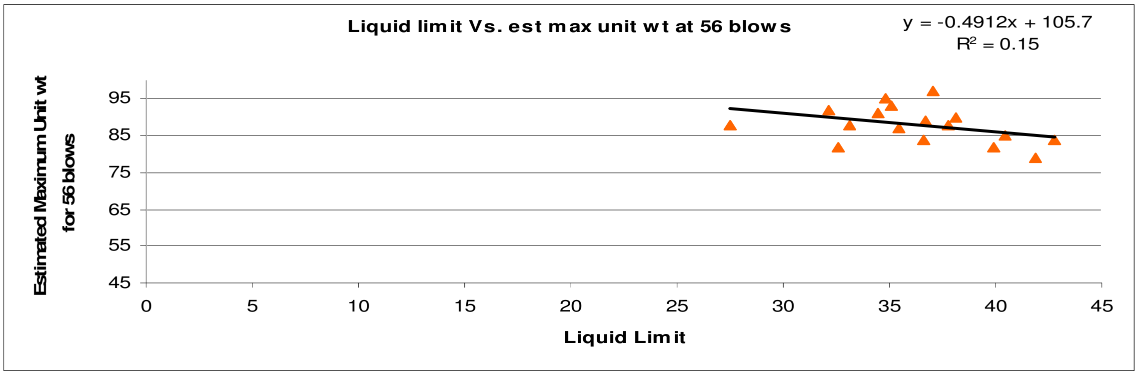

Figure B - 53. Liquid limit compared to maximum unit weight for highest compaction level.

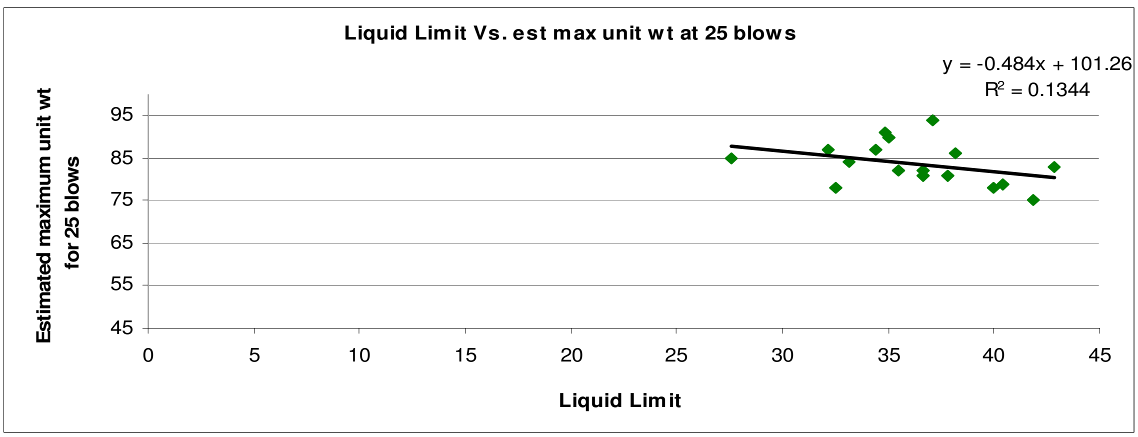

Figure B - 54. Liquid limit compared to maximum unit weight for middle compaction level.

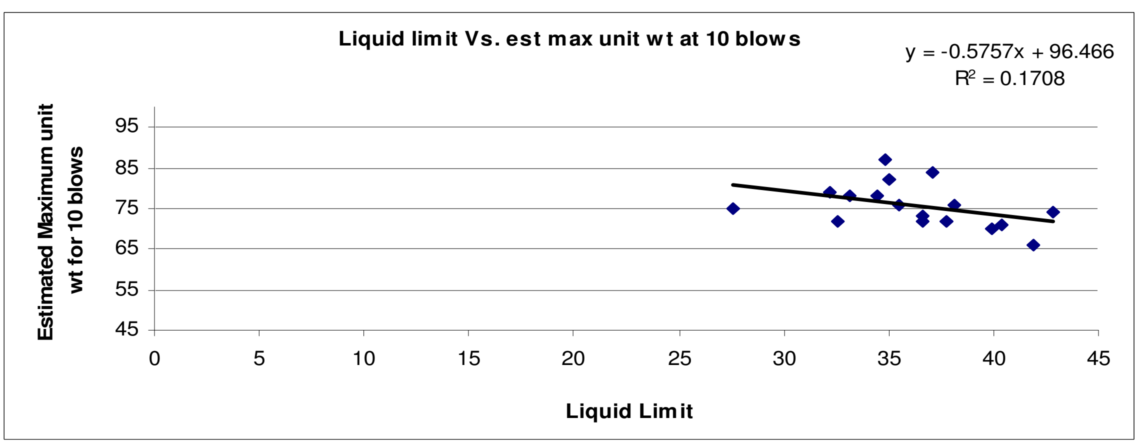

Figure B - 55. Liquid limit compared to maximum unit weight for lowest compaction level.

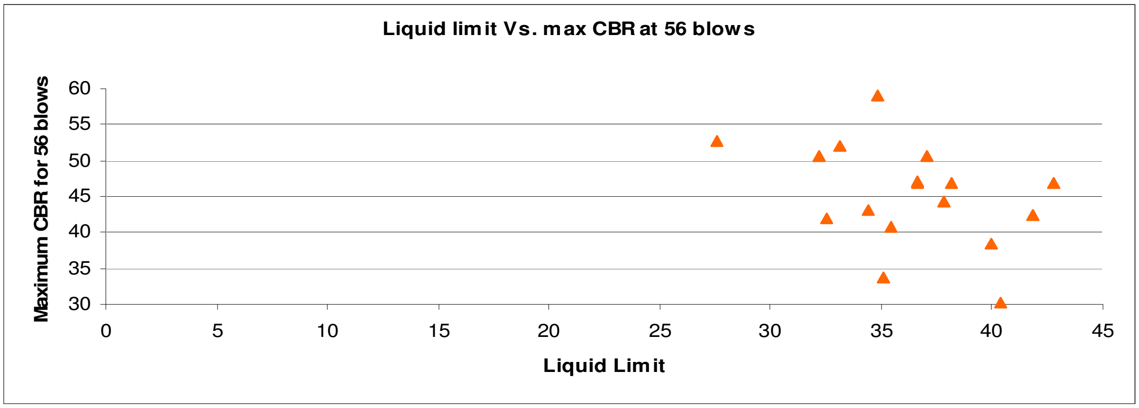

Figure B - 56. Liquid limit compared to maximum CBR for highest compaction level.

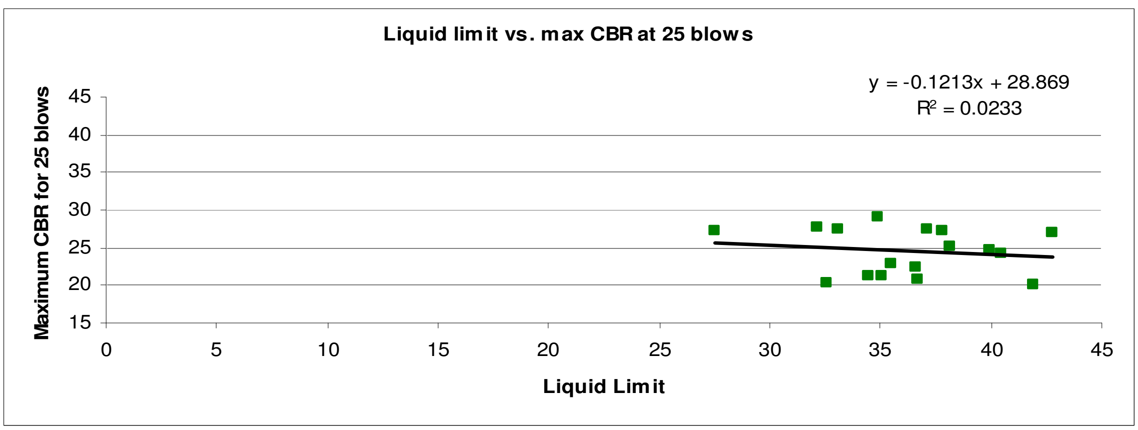

Figure B - 57. Liquid limit compared to maximum CBR for middle compaction level.

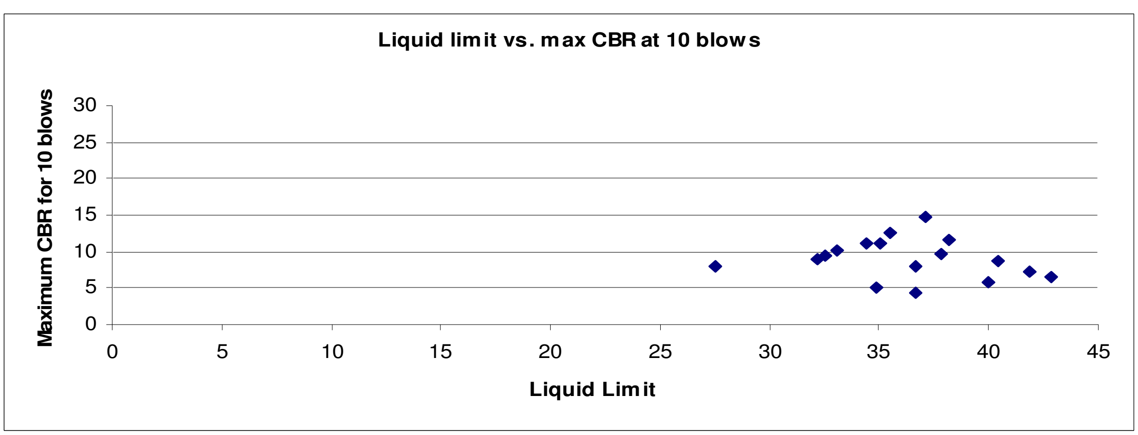

Figure B - 58. Liquid limit compared to maximum CBR for lowest compaction level.

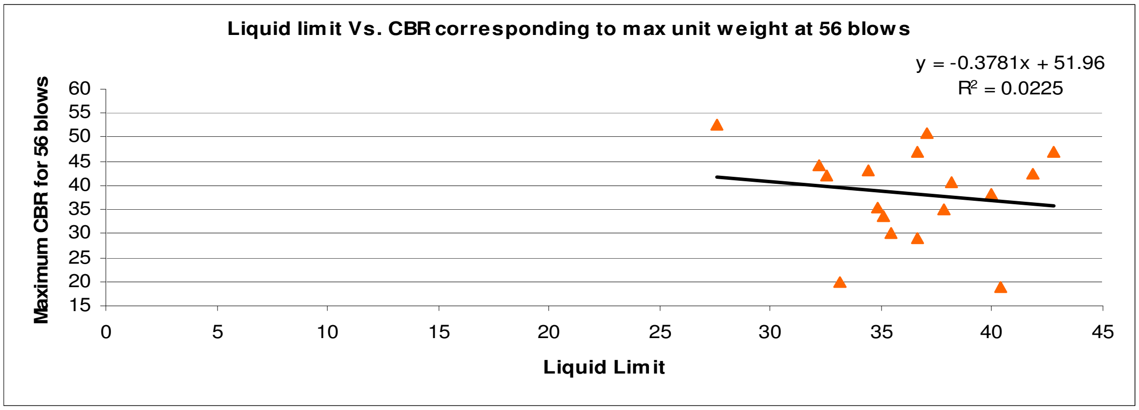

Figure B - 59. Liquid limit compared to CBR corresponding to the maximum unit weight for highest compaction level.

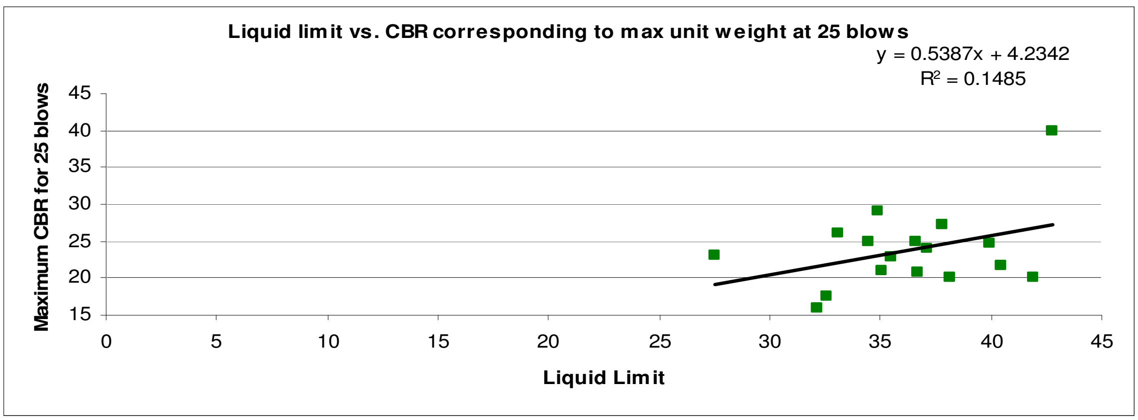

Figure B - 60. Liquid limit compared to CBR corresponding to the maximum unit weight for middle compaction level.

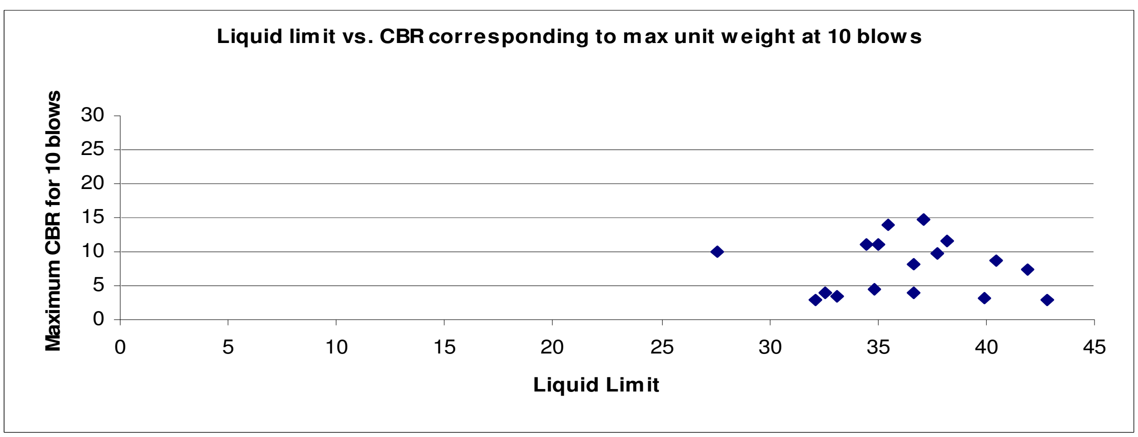

Figure B - 61. Liquid limit compared to CBR corresponding to the maximum unit weight for lowest compaction level.

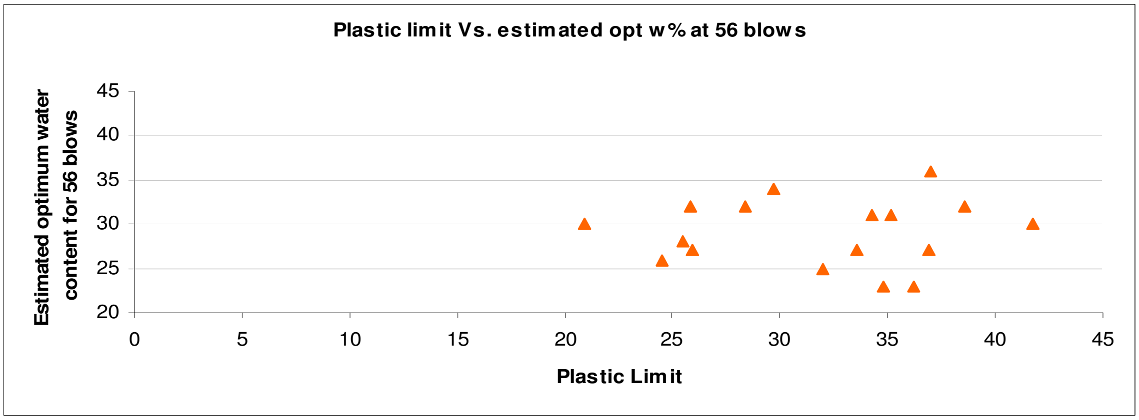

Figure B - 62. Plastic limit compared to optimum water content for highest compaction level.

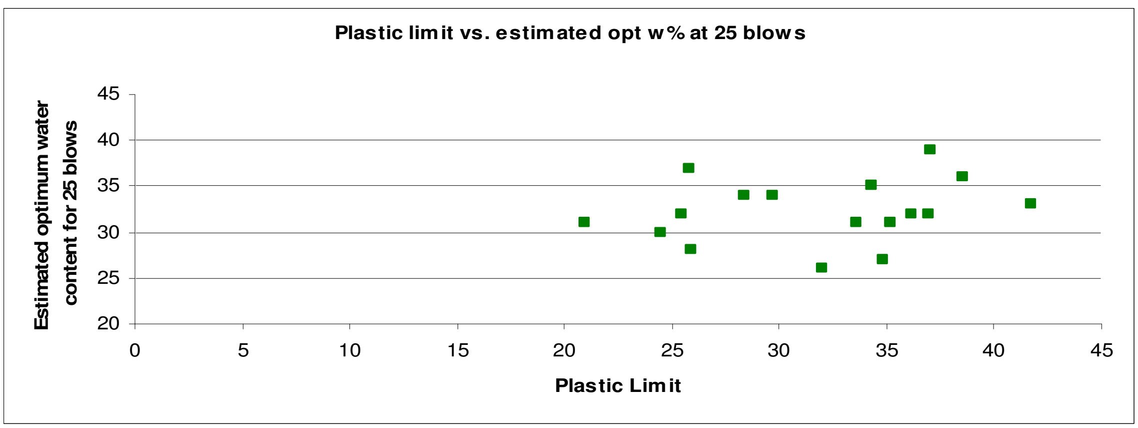

Figure B - 63. Plastic limit compared to optimum water content for middle compaction level.

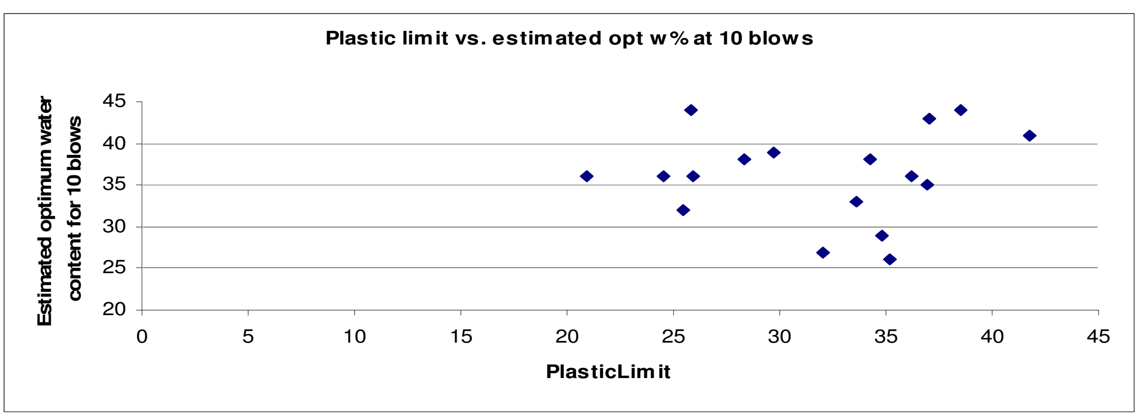

Figure B - 64. Plastic limit compared to optimum water content for lowest compaction level.

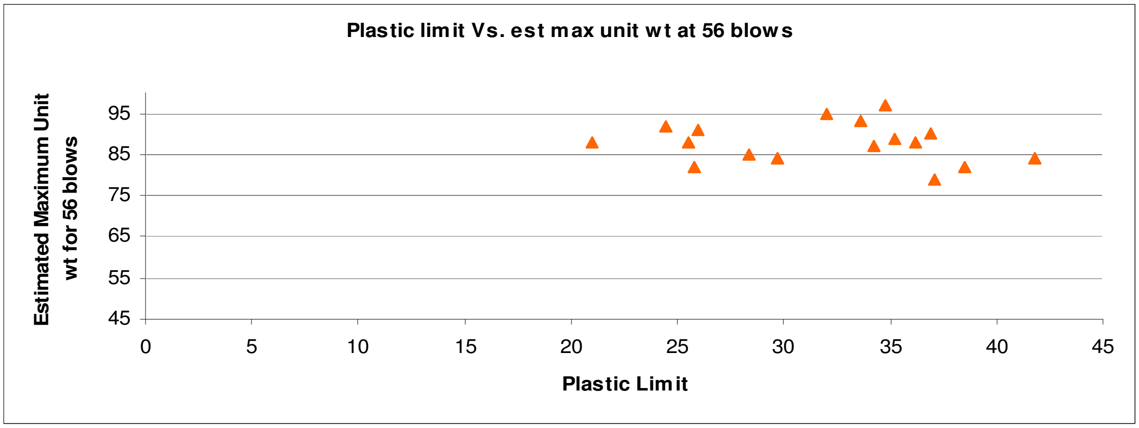

Figure B - 65. Plastic limit compared to maximum unit weight for highest compaction level.

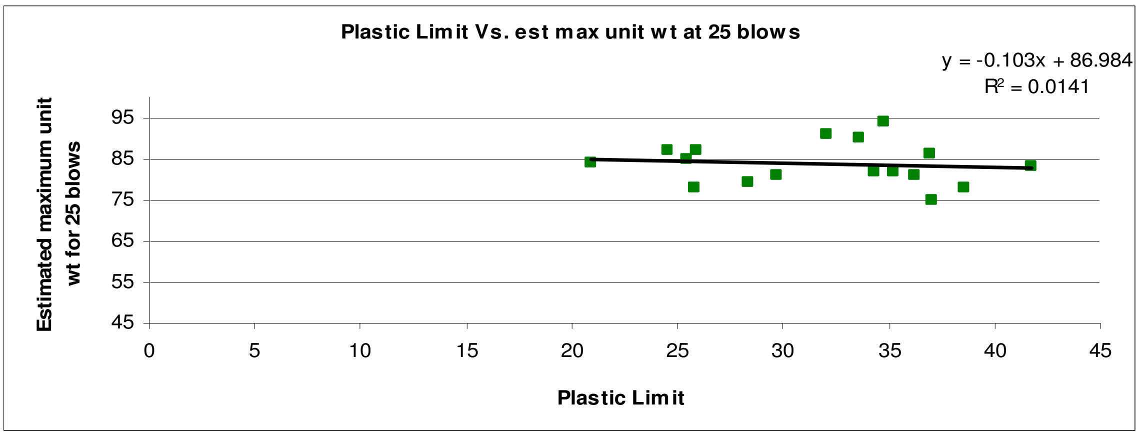

Figure B - 66. Plastic limit compared to maximum unit weight for middle compaction level.

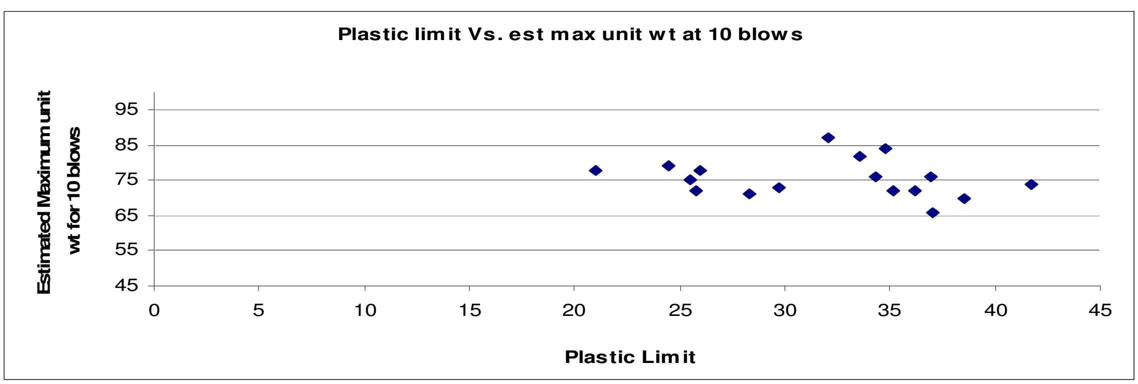

Figure B - 67. Plastic limit compared to maximum unit weight for lowest compaction level.

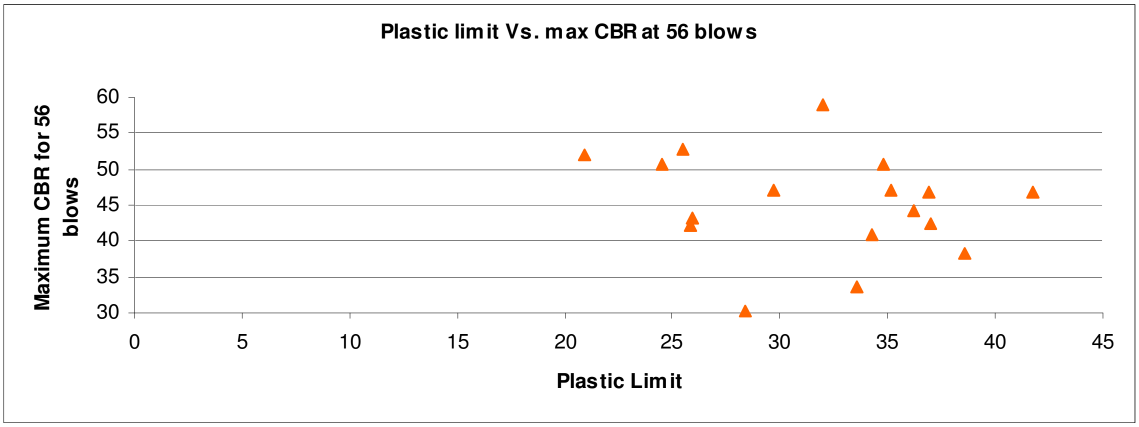

Figure B - 68. Plastic limit compared to maximum CBR for highest compaction level.

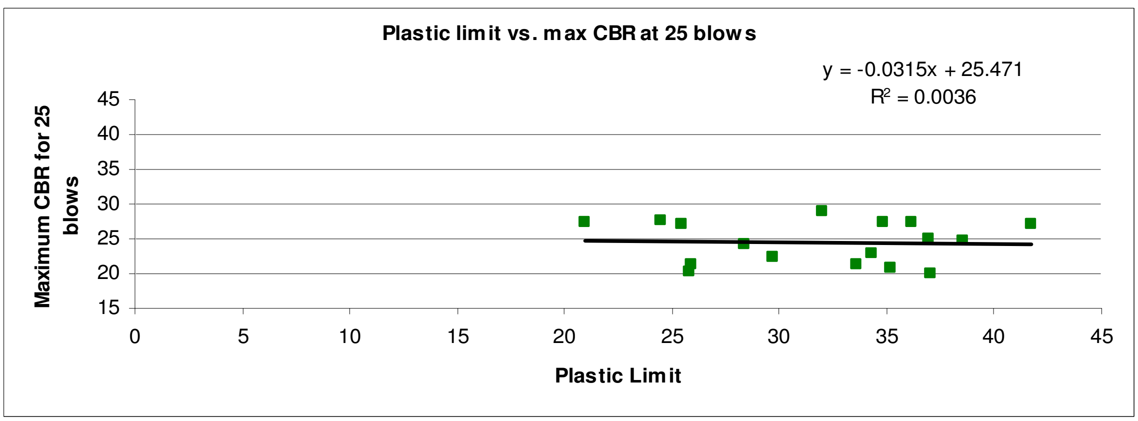

Figure B - 69. Plastic limit compared to maximum CBR for middle compaction level.

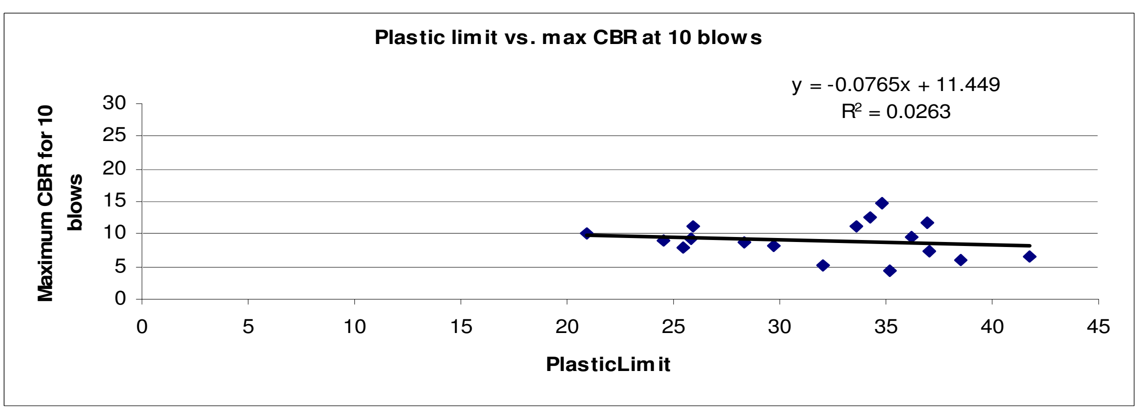

Figure B - 70. Plastic limit compared to maximum CBR for lowest compaction level.

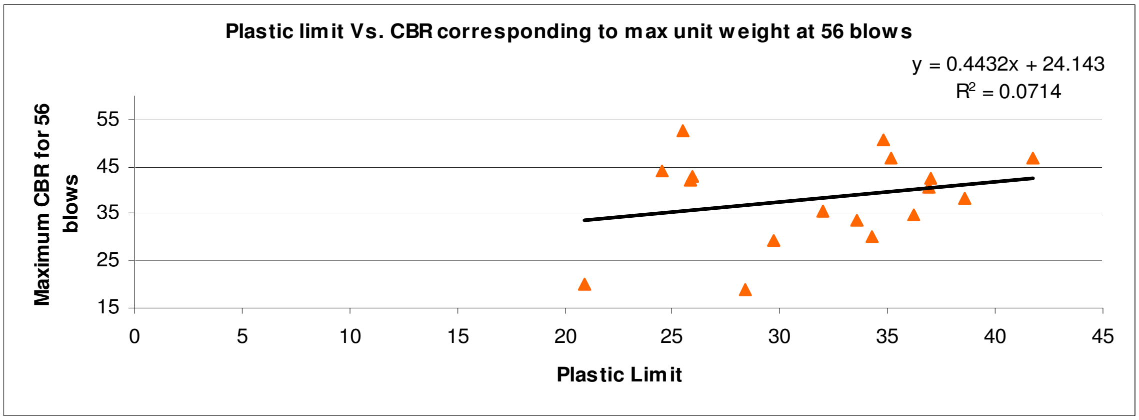

Figure B - 71. Plastic limit compared to CBR corresponding to maximum unit weight for highest compaction level.

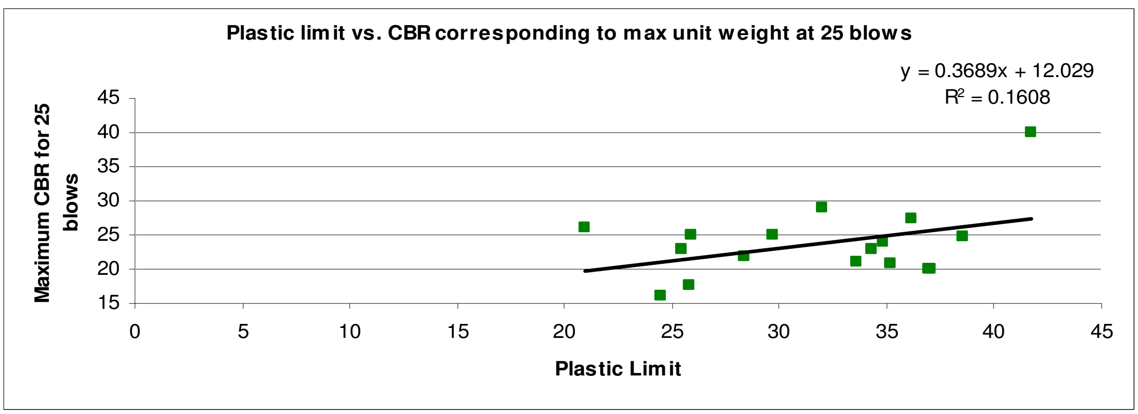

Figure B - 72. Plastic limit compared to CBR corresponding to maximum unit weight for middle compaction level.

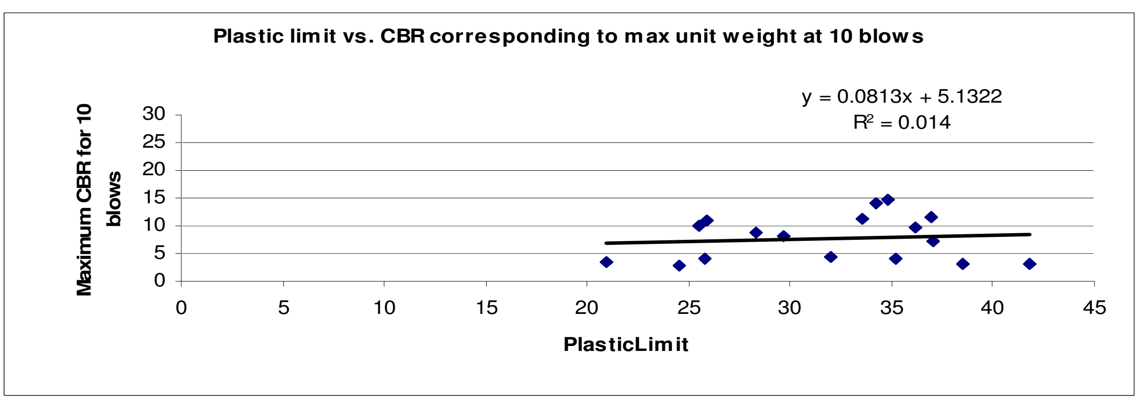

Figure B - 73. Plastic limit compared to CBR corresponding to maximum unit weight for lowest compaction level.

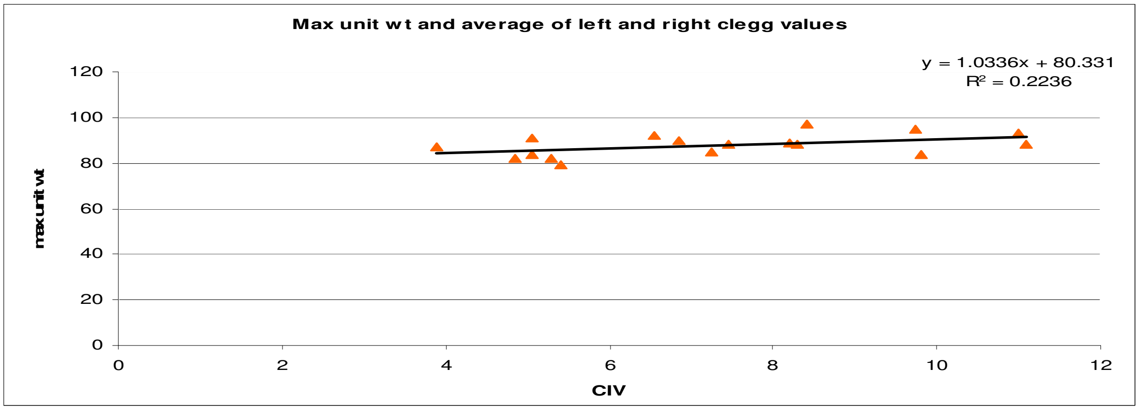

Figure B - 74. Clegg impact values compared to maximum unit weight for highest compaction level.

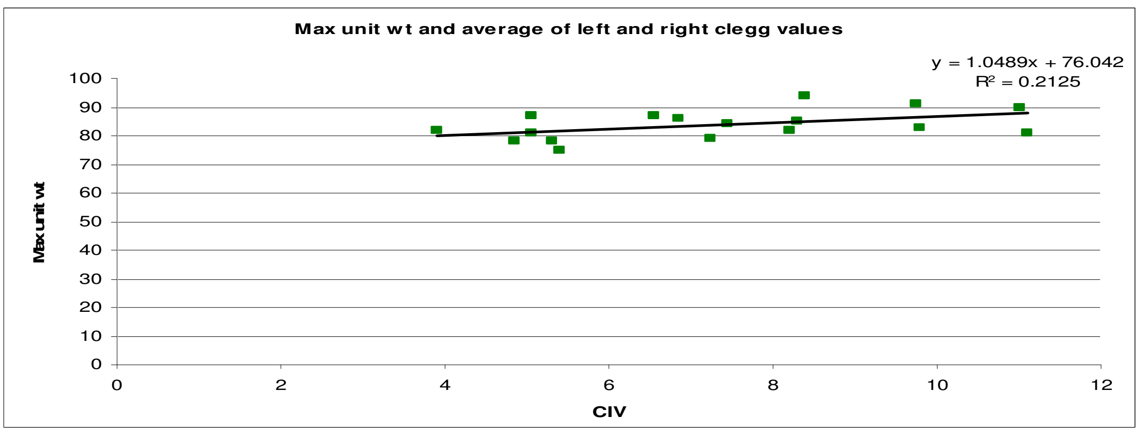

Figure B - 75. Clegg impact values compared to maximum unit weight for middle compaction level.

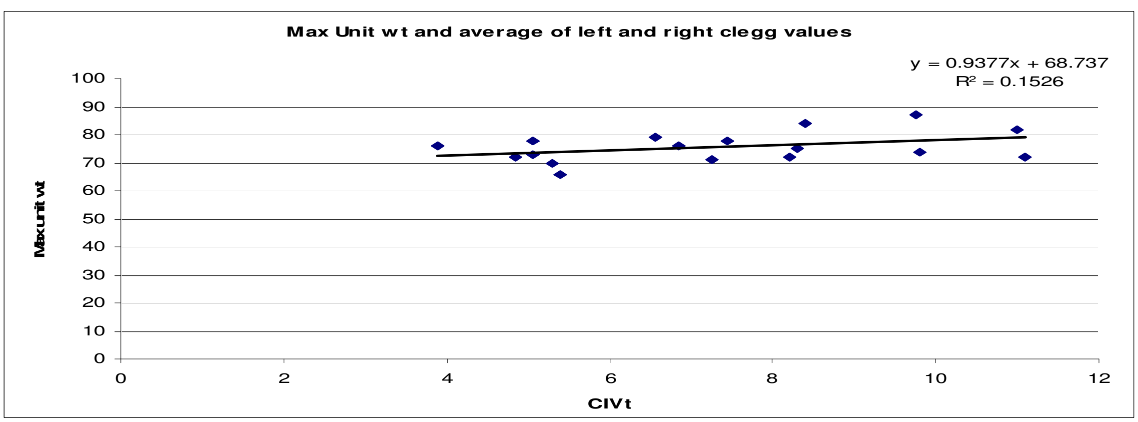

Figure B - 76. Clegg impact values compared to maximum unit weight for lowest compaction level.

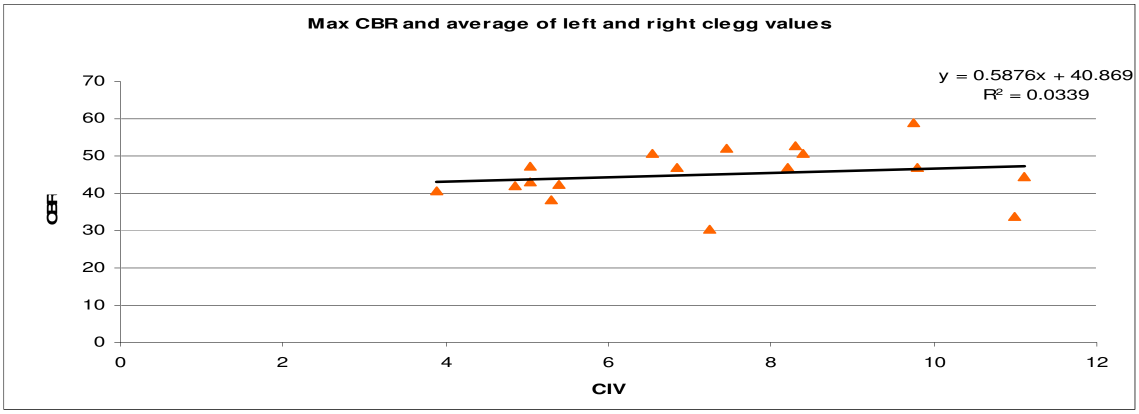

Figure B - 77. Clegg impact values compared to maximum CBR for highest compaction level.

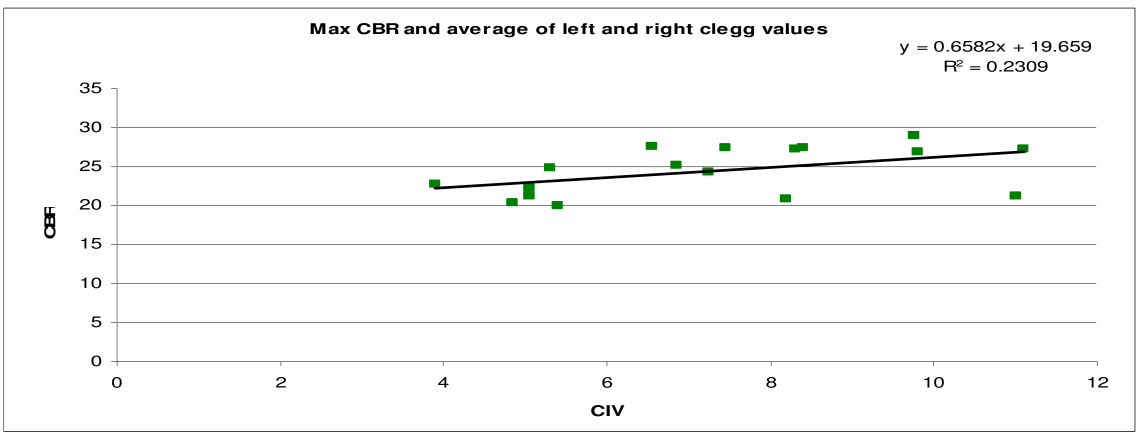

Figure B - 78. Clegg impact values compared to maximum CBR for middle compaction level.

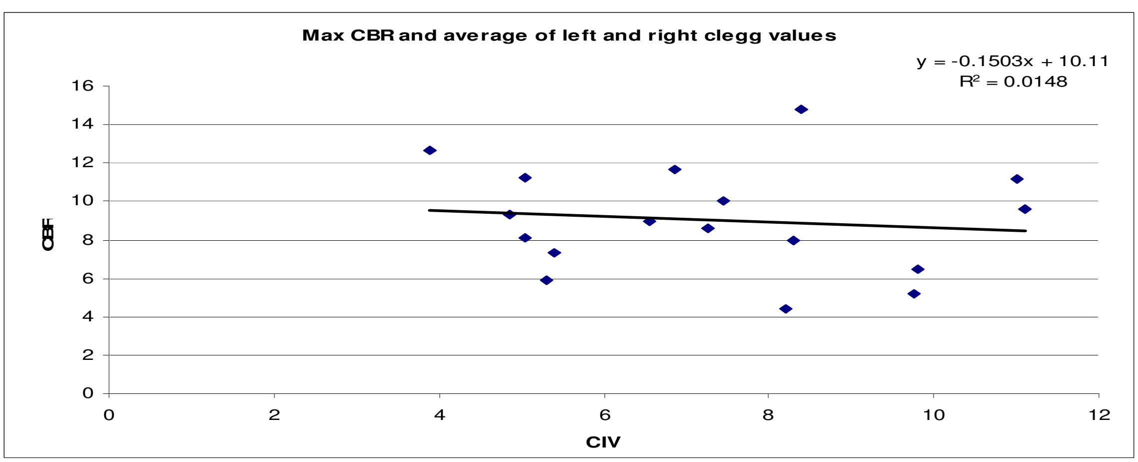

Figure B - 79. Clegg impact values compared to maximum CBR for lowest compaction level.

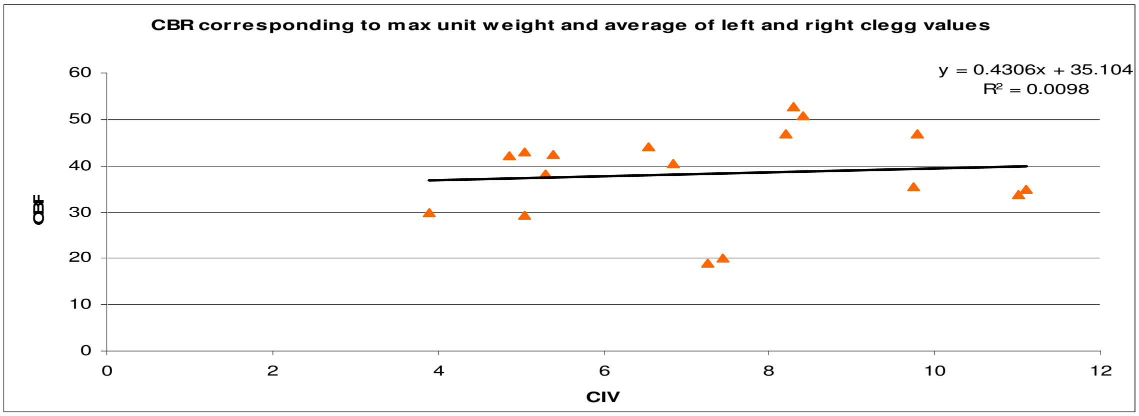

Figure B - 80. Clegg impact values compared to CBR corresponding to maximum unit weight for highest compaction level.

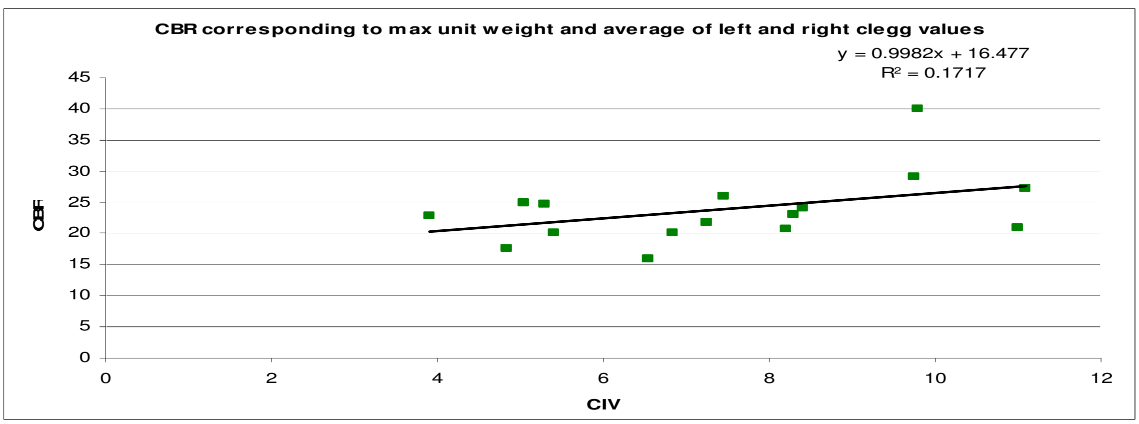

Figure B - 81. Clegg impact values compared to CBR corresponding to maximum unit weight for middle compaction level.

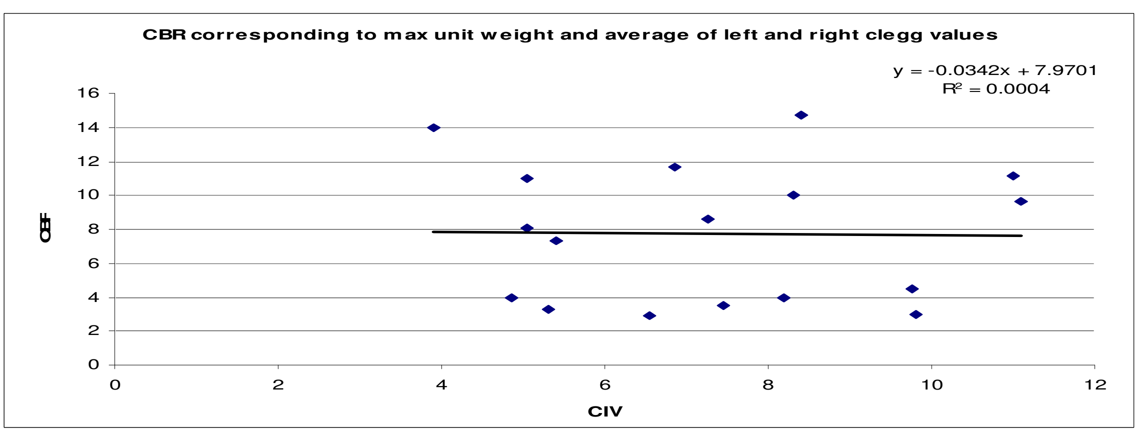

Figure B - 82. Clegg impact values compared to CBR corresponding to maximum unit weight for lowest compaction level.

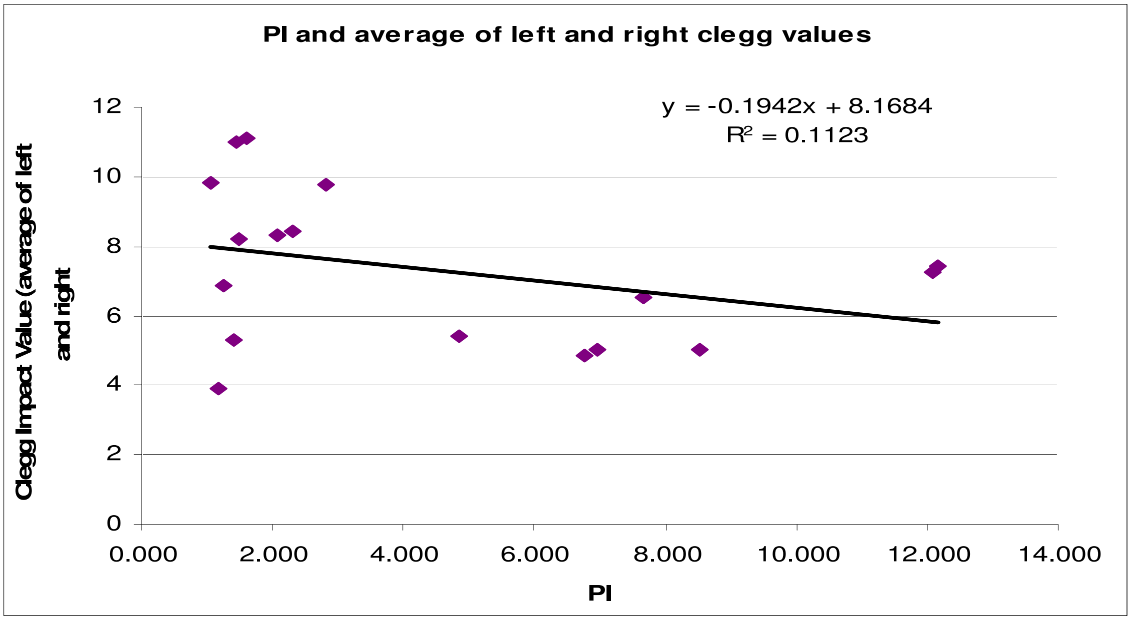

Figure B - 83. Plasticity index compared to Clegg impact values.

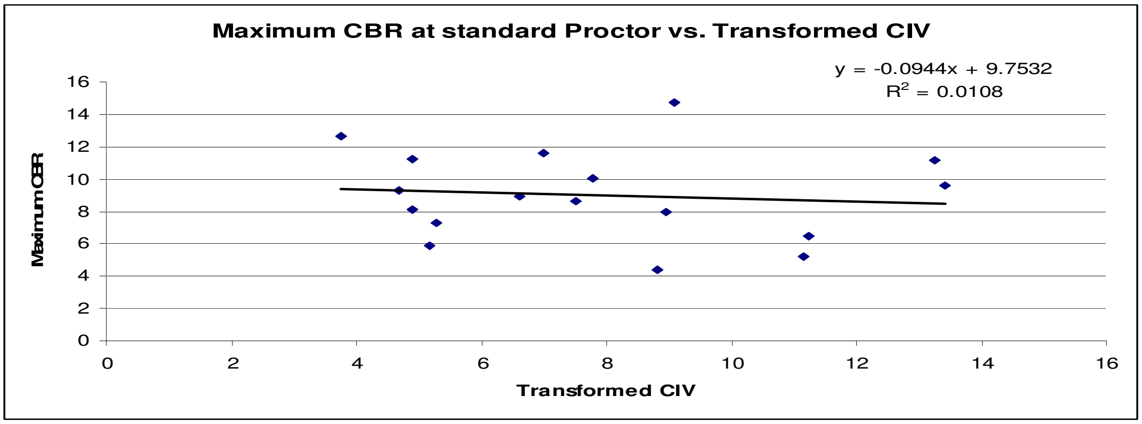

Figure B - 84. Maximum CBR at the standard Proctor level and Transformed CIV.

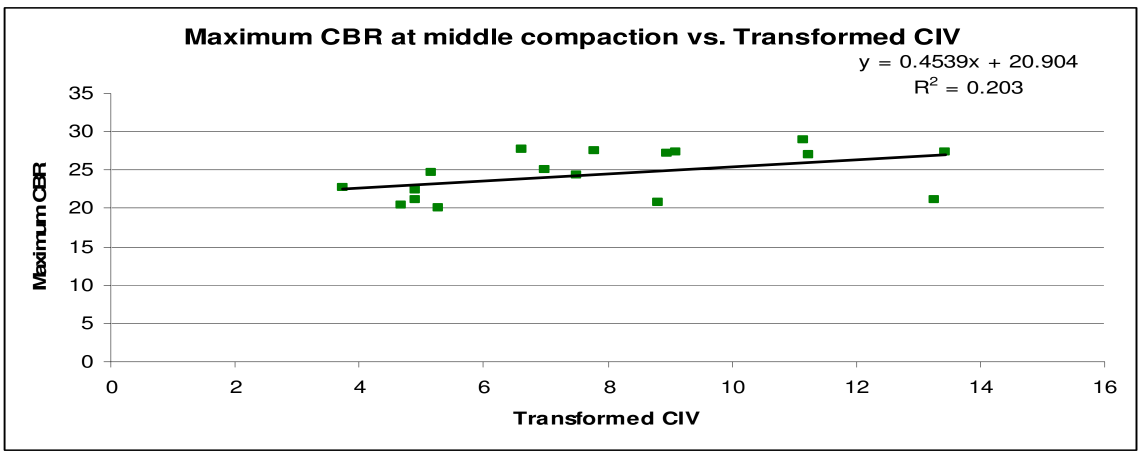

Figure B - 85. Maximum CBR at the middle compaction level and Transformed CIV.

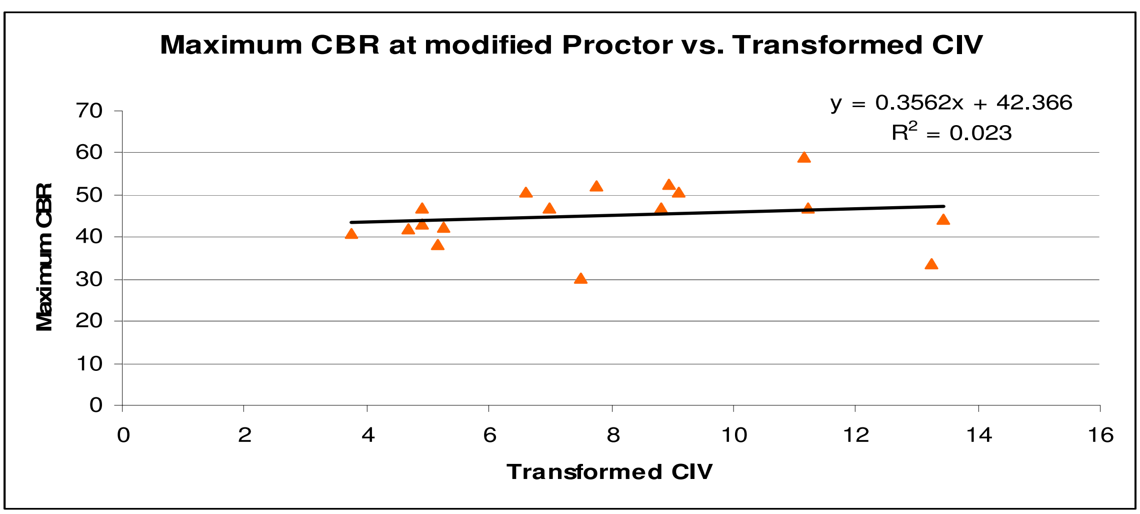

Figure B - 86. Maximum CBR at the modified Proctor level and Transformed CIV.

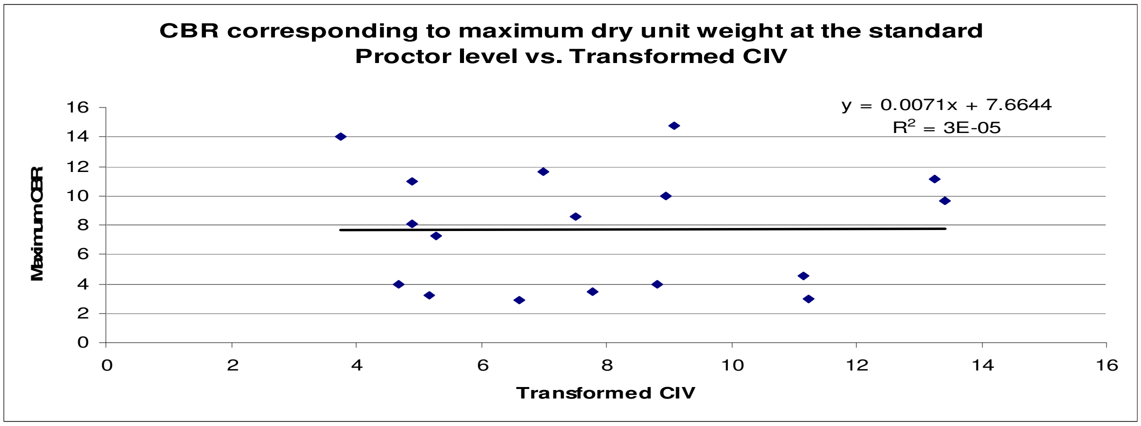

Figure B - 87. CBR at maximum dry unit weight at the standard Proctor level and Transformed CIV.

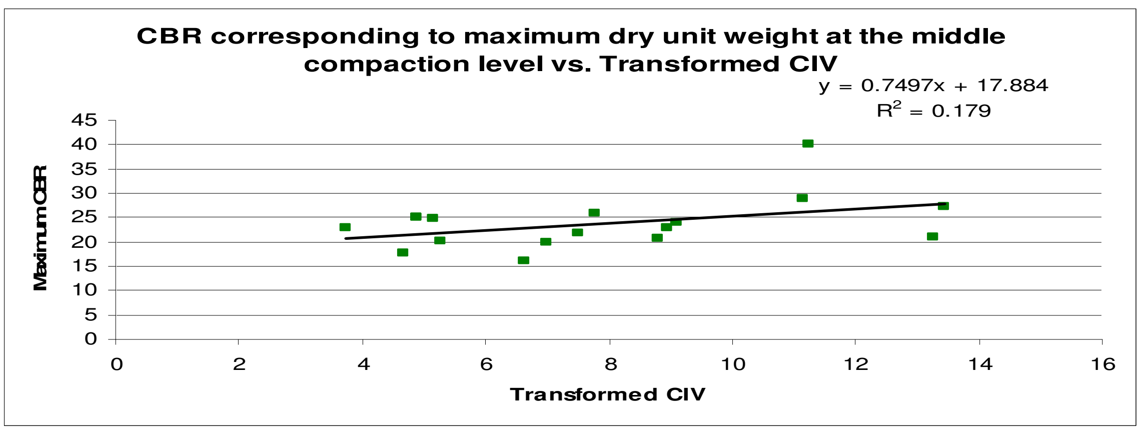

Figure B - 88. CBR at maximum dry unit weight at the middle compaction level and Transformed CIV.

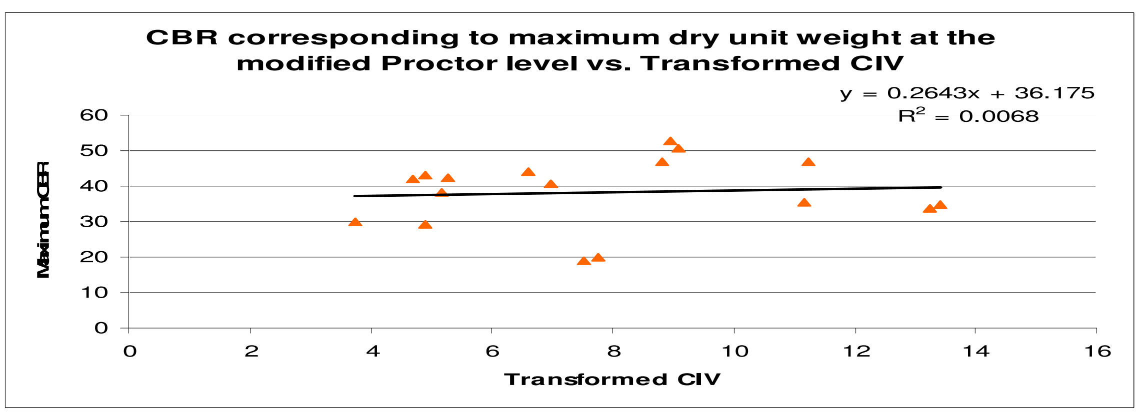

Figure B - 89. CBR at maximum dry unit weight at the modified Proctor level and Transformed CIV.

B.4.2 Significant Figures

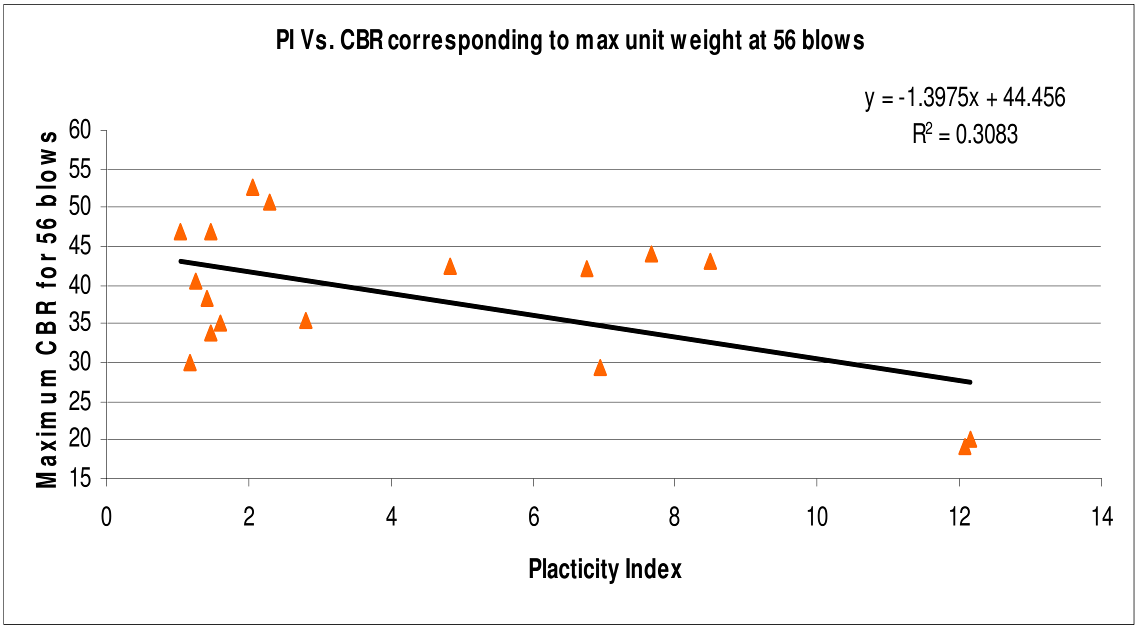

Figure B - 90. Plasticity Index compared to CBR corresponding to maximum unit weight for highest compaction level.

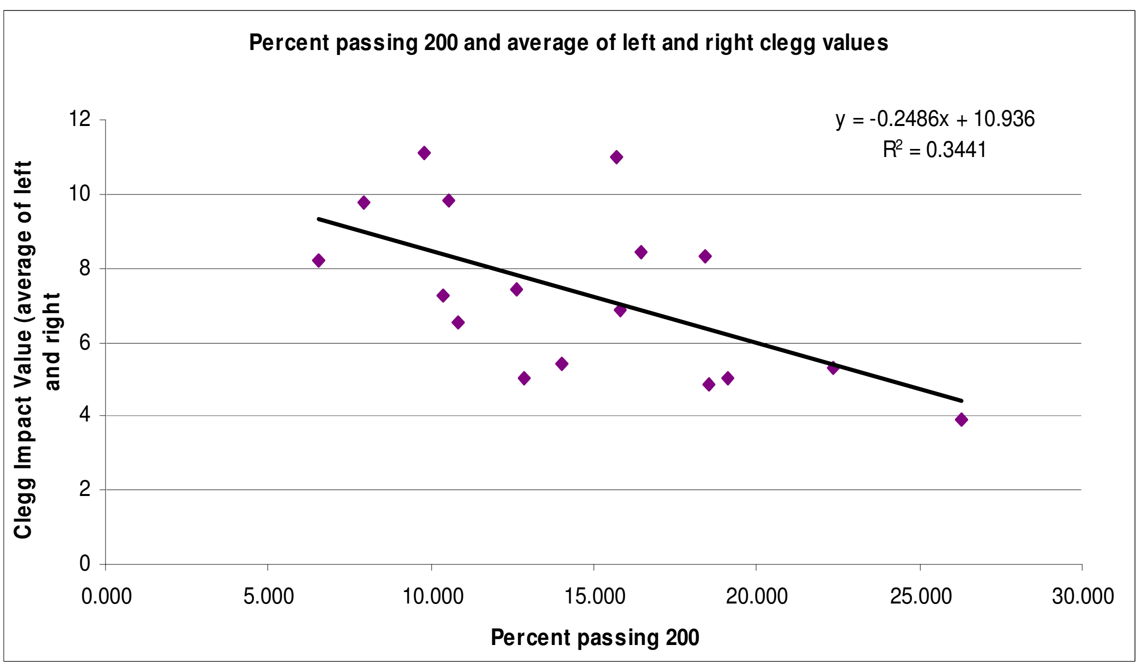

Figure B - 91. Percent passing No. 200 sieve compared to Clegg impact values.

Appendix C. Rut Model

Table C - 1. Road specifications based on study and maximum allowable rut depth for rut analysis

Road Specs			
Feet per station	300	ft	from study design
Total stations for new road	18	stations	from study design
New Road Length	1.02	mi	= sta/ft * sta / 5280
Road Width	14	ft	measured
Shoulder of road	1 1/2 : 1		assumed
Maximum allowable rut depth	1.5	in	assumed

Table C - 2. Traffic calculations based on volume of timber hauled on study road for the rut equation.

Trucking	Stinger Steered Standard Log Truck with Tire Pressure of 100 psi		
Total Volume to be Hauled	3500	mbf	estimated as part of study
Loaded			
single 10 kips	0.76		from table 3.2-5, USFS, 1996
dual 35 kips	2.27		from table 3.2-5, USFS, 1996
dual 35 kips	2.27		from table 3.2-5, USFS, 1996
load per truck	4.75	mbf/truck	assumed
total loaded trips	737	trips	= haul volume / mbf/truck
Traffic	3905.26		= sum of eswl's * trips
Unloaded			
single 10 kips	0.76		from table 3.2-5, USFS, 1996
dual 16 kips	0.51		from table 3.2-5, USFS, 1996
total unloaded trips	737	trips	= haul volume / mbf/truck
Traffic	935.79		= sum of eswl's * trips

Table C - 3. Assumed machine and labor costs for rut analysis

Equipment rates		
	Machine ($/hr)	**Operator ($/hr)**
Vibratory Roller	$42.87	$41.23
Water Truck	$28.26	$39.28
Grader	$30.99	$42.36

C.1 Assumptions and Equations Used for Soil Calculations

- Attainable Soil CBR = 95% of the average of the CBR corresponding to max unit wt for each compactive energy from the laboratory testing
  (average of the laboratory CBR values corresponding to max unit wt at standard Proctor level = 8, average of the laboratory CBR values corresponding to max unit wt at the middle compaction level = 24, average of the laboratory CBR values corresponding to max unit wt at modified Proctor = 38)

- Number of passes for low compaction = 4, according to Das (2002)

- Number of passes for Controlled compaction = (controlled compaction CBR * 4 passes for low compaction) / low compaction CBR = 22.8 * 4 / 7.6 = 12

- Number of passes for high compaction = (high compaction CBR * 4 passes for low compaction) / low compaction CBR = 36.1 * 4 / 7.6 = 19

- Volume of bottom subgrade lift = ((road width * depth + shoulder) * length) / 27
  Where, shoulder = (1.5 + .75) * .5 for 2 trapezoids for bottom layer of subgrade

- Volume of top subgrade lift = ((road width * depth + shoulder) * length) / 27
  Where, shoulder = (.75 * .5) for 2 triangles for top layer of subgrade

- Assume 2, 6-inch lifts are required

- Assume travel speed is 6 mph which is within the range specified in the CAT Handbook 2002

- Production rate of CAT 815 F (cy / hr) = 3765.3 / number of passes, according to CAT Handbook 2002

- Hours for compaction = (vol of bottom subgrade layer / production rate) + (vol of top subgrade layer / production rate)

- Machine Costs = 1.18 * (average equipment rates + operator costs)
  Where, 1.18 is the cost adjustment for 2006 according to the consumer price index, and equipment and operator rates from Wilbrecht, 2000

- Subgrade construction cost = hours for compaction * sum of machine costs

Table C - 4. Volume of soil subgrade to be compacted in two lifts

Soil	
Volume of bottom subgrade layer (cy)	1,625.00
Volume of top subgrade layer (cy)	1,475.00

Table C - 5. Cost and CBR calculations for rut analysis of three soil subgrade compaction levels

	Attainable Soil CBR	Number of passes required	Production Rate of CAT 815 F	hours for compaction	Cost of subgrade construction
Lowest compaction (standard)	7.6	4	941.33	3.29	$499.39
Controlled compaction (middle)	22.8	12	313.78	9.88	$1,498.17
Highly controlled compaction (modified)	36.1	19	198.17	15.64	$2,372.11

C.2 Assumptions and Equations Used for Aggregate Calculations

- Attainable Rock CBR = 2 * Soil CBR Based on the range suggested in USFS, 1996

- Rock depth = total of 12 inches to correspond with the surcharge weight used in laboratory CBR testing

- Base Rock Volume = ((road width * depth + shoulder) * length) / 27
  Where, shoulder = (1.5 + .75) * .5 for 2 trapezoids for base course aggregate

- Surface Rock Volume = ((road width * depth + shoulder) * length) / 27 Where, shoulder = (.75 * .5) for 2 triangles for surface aggregate

- Rock Cost =(base rock vol * $/cy for base coarse) + (surface rock vol * $/cy for surface coarse)

Table C - 6. Surface CBR calculations based on three soil subgrade compaction levels for rut analysis

Rock	
	Attainable Rock CBR
Lowest compaction (standard Proctor)	15.2
Controlled compaction (middle)	45.6
Highly controlled compaction (modified Proctor)	72.2

Table C - 7. Surface cost calculations for both base coarse aggregate and surface aggregate for rut analysis

Rock				
	Cost per cy	**depth**	**Rock Volume (cy)**	**Total Rock Cost for road**
Base Course = 3" minus	8	0.5	1625.00	$14,487.00
Surface = 3/4" minus	12	0.5	1475.00	

C.3 Assumptions and Equations Used for Analysis of Rut Depth

- Total cost = subgrade construction cost + rock cost
- Rut Depth = 0.1741 * (((ESWL $^{0.4704}$) * (tire pressure $^{0.5695}$) * (traffic $^{0.2476}$)) / ((LOG(rock depth) $^{2.002}$) * (surface CBR $^{0.9335}$) * (subgrade CBR $^{0.2848}$)))
  Where, ESWL = 8.64 kips and tire pressure = 80 psi from USFS, 1996
- Acceptable solution = total cost IF rut depth < allowable rut depth
- If rut depth > allowable rut depth then maintenance is required
- Total cost after maintenance = total cost + maintenance cost

Table C - 8. Final cost calculations for rut model for three soil compaction levels

Subgrade Compaction	**Total Cost**	**Rut Depth**	**Acceptable Solution**	**Total Cost after maintenance (if needed)**
Standard	$14,986.39	1.81	not acceptable	$20,167.73
Middle	$15,985.17	0.47	$15,985.17	$15,985.17
Modified	$16,859.11	0.27	$16,859.11	$16,859.11

C.4 Assumptions and Equations Used for Maintenance Calculations

- Grader requires 3 passes per road segment for proper maintenance
- Grader travels at 6 Mph in 4th gear according to http://www.equipmentcentral.com/north_america/new_equipment/machine_data.cfm?cfid=1118933&cftoken=58449088&prdt_id=649&body=full_specs.cfm
- Hours for maintenance = number of passes * total road length / 6 Mph
- Machine Costs = 1.18 * (average equipment rates + operator costs)
  Where, 1.18 is the cost adjustment for 2006 according to the consumer price index, and equipment and operator rates from Wilbrecht, 2000

- Assume replacement rock depth = rutting depth

- Replacement Rock Volume = ((road width * replacement rock depth + shoulder) * length) / 27
  Where, shoulder = (1.5 * rock replacement depth) * rock replacement depth for 2 triangles for surface aggregate

- Maintenance rock cost = volume of replacement rock * surface rock cost per cy

- Maintenance cost = (hours for maintenance * sum of machine costs) + maintenance rock cost

Table C - 9. Maintenance cost calculations for rut model based on rutting depth to be repaired

Maintenance				
hours to maintain road	**equipment and labor**	**replacement rock depth (ft)**	**volume of replacement rock**	**Maintenance cost**
0.51	37.51	0.151	428.65	$5,181.34
		0.040	111.10	$1,370.69
		0.023	63.36	$797.77